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RESEARCH ARTICLE

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The importance of biochar quality and pyrolysis yield for soil carbon sequestration in practice

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Abstract

Biochar is a carbon (C)-rich material produced from biomass by anoxic or oxygen-limited thermal treatment known as pyrolysis. Despite substantial gaseous losses of C during pyrolysis, incorporating biochar in soil has been suggested as an effective long-term option to sequester CO_2 for climate change mitigation, due to the intrinsic stability of biochar C. However, no universally applicable approach that combines biochar quality and pyrolysis yield into an overall metric of C sequestration efficiency has been suggested yet. To ensure safe environmental use of biochar in agricultural soils, the International Biochar Initiative and the European Biochar Certificate have developed guidelines on biochar quality. In both guidelines, the hydrogen-to-organic C (H/C_{org}) ratio is an important quality criterion widely used as a proxy of biochar stability, which has been recognized also in the new EU regulation 2021/2088. Here, we evaluate the biochar C sequestration efficiency from published data that comply with the biochar quality criteria in the above guidelines, which may regulate future large-scale field application in practice. The sequestration efficiency is calculated from the fraction of biochar C remaining in soil after 100 years (F_{perm}) and the C-yield of various feedstocks pyrolyzed at different temperatures. Both parameters are expressed as a function of H/C_{org}. Combining these two metrics is relevant for assessing the mitigation potential of the biochar economy. We find that the C sequestration efficiency for stable biochar is in the range of 25%–50% of feedstock C. It depends on the type of feedstock and is in general a non-linear function of H/C_{org}. We suggest that for plant-based feedstock, biochar production that achieves H/C_{org} of 0.38–0.44, corresponding to pyrolysis temperatures of 500–550°C, is the most efficient in terms of soil carbon sequestration. Such biochars reveal an average sequestration efficiency of 41.4% (±4.5%) over 100 years.

KEYWORDS

biochar certification, carbon farming, H/C ratio, permanence, persistence, sequestration efficiency, soil amendment

1 | INTRODUCTION

Soil carbon (C) sequestration is widely recognized as a negative CO_2 emission technology that can contribute to the mitigation of climate change (Lal, 2004; Pires, 2019). In this context, the use of biochar as a soil amendment is gaining attention as an efficient measure to sequester C in soil (Amelung et al., 2020; Rodrigues et al., 2021; Schmidt et al., 2021; Sohi et al., 2009; Woolf et al., 2010). Biochar is produced from biomass by anoxic or oxygen-limited thermal treatment known as pyrolysis (Lehmann & Joseph, 2015), and the resulting carbonaceous product has a high stability due to the prevalence of fused aromatic ring structures. However, biochar can be produced from different feedstocks, and under varying pyrolysis conditions, which jointly result in different physicochemical properties that affect the stability of biochar in terms of its persistence in soil. The term biochar is collectively used to describe charred organic matter produced on purpose for improvement of soil properties and ecosystem services after application directly or indirectly, for example with animal excreta after having been used as a feed additive (Lehmann & Joseph, 2015). However, the high variability of biochar physicochemical properties suggests that production and use of biochar need to be adapted to each situation and for each purpose (Al-Wabel et al., 2018).

In the last decade, increasing efforts have been made to understand how different biochar and soil properties affect the resulting stability in terms of biochar resistance to decomposition in soil (Al-Wabel et al., 2018; Lehmann & Joseph, 2015; Wang et al., 2016; Zimmerman & Gao, 2013). The comprehensive review by Al-Wabel et al. (2018) on the impact of biochar properties on soil conditions indicates that biochar produced at low temperature may increase soil fertility and crop yields, whereas high-temperature biochar may be better suited to improve long-term soil C sequestration. High-temperature biochars (>400°C) are characterized by relatively low hydrogen to organic C (H/C_{org}) molar ratios (0.2–0.6) and exhibit higher stability than materials charred at low temperature with resulting higher molar ratio ($H/C_{org} > 0.6$) (Schimmelpfennig & Glaser, 2012). Thus, the H/C_{org} molar ratio has been widely recognized as a suitable proxy to describe biochar stability in science and in practice. The European Biochar Certificate (EBC) for instance states that the H/C_{org} molar ratio is the most important characteristic to determine the C-sink value of biochar (EBC, 2012–2022). The EBC follows the International Biochar Initiative (IBI) guidelines with additional regulations and gives a framework to sustainable biochar production and low hazard use in agriculture (IBI, 2015). The H/C_{org} molar ratio is also listed as a parameter in the new EU regulation 2021/2088 that lays down rules on the market of EU fertilizing products (EU, 2021).

Highlights

- A comprehensive metric is suggested for assessing the C sequestration efficiency of biochar.
- C sequestration efficiency combines pyrolysis carbon yield and biochar stability in soil.
- 25%–50% of carbon originally in feedstock for pyrolysis remains in soil after 100 years.
- Highest C sequestration efficiency is found for pyrolysis temperatures of 500–550°C.

The persistence of biochar in soils has been studied during the last 20 years in a large number of incubation- and field experiments, accompanied by a growing number of reviews on this topic (Lehmann & Joseph, 2015; Wang et al., 2016; Zimmerman & Gao, 2013). Based on the available data, biochar mean residence times (MRT) were modelled, with estimates ranging from 3 to 891 years (Wang et al., 2016). The wide range of MRTs can be explained by the diversity of experimental set-ups used in different studies. Among the most important factors are duration of the experiment, type of experiment (laboratory and field), soil type (mineralogy and texture), climate (temperature and moisture) and biochar properties, the latter being mostly a function of pyrolysis temperature and feedstock (Wang et al., 2016). Among the biochar properties, the H/C_{org} ratio has been shown to be a relatively robust parameter to estimate the MRT in different kinds of environments (Lehmann & Joseph, 2015). Woolf et al. (2021) proposed an easily applicable methodology to estimate C sequestration for biochar application by which the fraction of biochar C remaining in soil after 100 years (F_{perm}) is estimated as a function of H/C_{org} or pyrolysis temperature without requiring detailed information about soil properties or environmental conditions except for soil temperature.

Adhering to the guidelines of the EU, IBI and EBC, the type of feedstock used for biochar production and certain physicochemical properties of biochar (e.g., elemental composition, grain size) have to be documented for certification of biochar to be used in practice. In particular, thresholds of biochar molar ratios should not exceed 0.7 for H/C_{org} and 0.4 for O/C_{org}. The reason for that is that molar ratios are material properties that relate to the degree of thermochemical alteration responsible for the increasing fused aromatic ring structures in the material and the resulting stability (Keiluweit et al., 2010). The upper limit is used to distinguish biochar from biomass that has only been slightly thermochemically altered

(IBI, 2015). In other words, H/C_{org} molar ratios greater than 0.7 are an indicator of pyrolysis deficiencies or even the presence of nonpyrogenic carbon. Uncharred lignin, for instance, is characterized by H/C_{org} of between 0.7 and 1.5 (Schimmelpfennig & Glaser, 2012). Accordingly, the criterion of $H/C_{org} < 0.7$ is key in the definition of biochar and other gasification and pyrolysis products in the EU Regulation 2021/2088 of 7 July 2021 (EU, 2021) amending the EU Regulation 2019/1009 (EU, 2019) by defining 'pyrolysis and gasification materials as a component material category in EU fertilising products'. This new regulation opens European markets to biochars since 16 July 2022, which is a huge step forward in the perspective of generalizing the use of biochar as a soil amendment to tackle climate change. In that context, guidelines for an optimal use of biochar in terms of agro-environmental benefits and soil C sequestration are urgently needed.

The overall C sequestration potential of biochar not only depends on its stability but also depends on the C-yield of the pyrolysis process. While many studies focus on mass yield of different biochar production processes (Almutairi et al., 2023; Al-Wabel et al., 2018; Demirbas, 2004; Tomczyk et al., 2020; Tripathi et al., 2016), only a handful of studies point to the importance of the C-yield to estimate the potential of C sequestration of biochar (Lehmann et al., 2006; Zhao et al., 2013). In general, these studies found that the biochar yield by mass decreases with increasing highest treatment temperature (HTT), whereas the C-yield seems to be more affected by the feedstock and is less sensitive to HTT (Lehmann et al., 2006; Mašek et al., 2013; Mukome et al., 2013; Zhao et al., 2013). A systematic study including different feedstocks and pyrolysis conditions to evaluate the relationship between degree of carbonization (H/C_{org}) and C-yield is still missing, however. Understanding this relationship is not only crucial to estimate C sequestration for different qualities of biochar but also to optimize pyrolysis conditions (e.g., temperature and feedstock) for production.

The aim of this study was to bridge the gap between research and practice for biochar stability and soil C sequestration estimations considering biochar quality and properties that are in accordance with biochar on the market. To do so, we selected studies where the biochar properties are in accordance with the IBI and EBC criteria in terms of C_{org} content, H/C_{org} and O/C_{org} ratios. Our objectives are (1) to provide an empirical approach for estimating the change in soil organic C stocks from biochar amendments that agree with biochar used in practice; (2) to assess the relationship and possible trade-offs between biochar stability and C-yield for different feedstocks; and (3) to evaluate the effect of stability and C-yield on C sequestration efficiency and permanence of biochar in soils.

2 | MATERIALS AND METHODS

2.1 | Data and selection criteria

We develop and combine two independent data sets: one describing biochar stability, and the other describing the C-yield of pyrolysis. These data were extracted after an extensive literature search of peer-reviewed publications reporting C-yields as a function of feedstock and temperature that also include C_{org} content, H/C_{org} ratio and, for calculating F_{perm}, biochar stability. We selected only data where biochars complied with the guidelines of IBI and EBC in terms of C_{org} content (≥50%), H/C_{org} ratio (<0.7) and O/C_{org} ratio (<0.4). Overall, 77 data points were included for calculating biochar stability, and 140 data pairs (i.e., before and after pyrolysis) for quantifying the net C-yield of pyrolysis. Three studies documented H/C_{org} versus pyrolysis temperature before and after pyrolysis but without providing C-yields.

2.2 | Biochar stability to decomposition in soil (F_{perm})

A model was developed for biochar resistance to decomposition as a function of its property to infer biochar stability in soil. It is based on an already suggested methodology, whereby the fraction of biochar C remaining in the soil after 100 years (F_{perm}) was used as an indicator of biochar stability and was related to H/C_{org} or HTT. This methodology was first suggested by IPCC (IPCC, 2019), and modified by Woolf et al. (2021). The relationship is based on empirical data from field and incubation studies (Budai et al., 2016; Dharmakeerthi et al., 2015; Fang et al., 2014; Fang et al., 2019; Herath et al., 2015; Liu et al., 2020; Major et al., 2010; Singh et al., 2012; Singh et al., 2015; Wu et al., 2016; Zimmerman, 2010; Zimmerman & Gao, 2013), that provided a minimum of 1 year of mineralization data. Since biochar is a complex matrix, its long-term decomposition is best described using a multipool decay function, with at least two pools (with slow and fast mineralization rates), rather than a single-pool model. Accordingly, Woolf et al. (2021) determined F_{perm} by fitting a two-pool exponential decay model to the data sets (or, in a single case using a three-pool model):

$$C_{(t)} = p_1 e^{(-k_1 * t)} + p_2 e^{(-k_2 * t)} \quad (1)$$

where the amount of carbon C remaining after time $C_{(t)}$ is a function of the size of a labile and stable pool p_1 and p_2, respectively, and their corresponding decomposition rate constants k_1 and k_2. Accordingly, $C_{(t=100\text{years})} = \text{F}_{\text{perm}}$.

In addition to data already compiled by Woolf et al. (2021), we added the results from a biochar incubation study recently published by Aubertin et al. (2021). Following the same approach and criteria as Woolf et al. (2021), a two-pool model was fitted to their mineralization data of 1 year of incubation (Supplementary Table S1).

Samples from the various studies were incubated at different temperatures. Woolf et al. (2021) normalized the rate constants to the global mean annual cropland temperature of 14.9°C using the temperature dependency of biochar decomposition (Q_{10}) as suggested by Lehmann et al. (2015):

$$Q_{10} = 1.1 + 12.0e^{-0.19T} \tag{2}$$

with T—incubation temperature (°C). Here, incubation data from Aubertin et al. (2021) were likewise normalized to 14.9°C according to Equation (2).

This approach thereby follows rigorous selection criteria for biochar incubation studies as proposed by Leng et al. (2019). The final data used in this study included one field experiment and 12 laboratory experiments. It encompasses data from 19 different feedstocks, that is six from wood, 11 from nonwood and two from papermill sludge and poultry litter (here designated as 'other'). The nonwood feedstocks include grasses, straw and crop residues.

2.3 | Biochar properties and carbon yield of pyrolysis

The two most important factors determining biochar properties and yield are HTT and type of feedstock. There is a wide variety of feedstocks used to produce biochar including wood, grass and different kinds of biomass waste (e.g., rice husks, peanut shells, fruit peels, sewage sludge and manures). The use of feedstock for biochar production often depends on what is locally available and allowed to be used. For application in practice and in accordance with the EBC, any biomass type that is on the *positive list* (EBC, 2012–2022) may be used individually or in combination. To fit the EU Regulation 2019/1009 (EU, 2019) and its amendment 2021/2088 (EU, 2021), the following feedstocks are prohibited: materials originating from mixed municipal waste, sewage sludge, industrial sludge or dredging sludge, and animal by-products or derived products within the scope of EC Regulation No. 1069/2009 (EC, 2009). For our study, we used the data sets reviewed by Al-Wabel et al. (2018), plus additional four contributions (Bai et al., 2013; Demirbaş, 2001; Gibson et al., 2018; Zhang et al., 2017). Together, these studies cover a wide range of biochar yields, physicochemical properties, such as H/C_{org} molar ratios and C_{org} of the produced biochars, and, in many cases, C_{org} of the feedstock (% dry matter). In cases where information on C_{org} of the feedstock was not provided in the publication ($n = 15$), standard values for the respective feedstocks were taken from IPCC (1996). In total, 140 data pairs from 27 studies were gathered, which encompassed 20 different feedstocks of which 10 are nonwood and 10 are different types of wood (for details, please see Supplementary Table S2).

2.4 | Biochar C-yield and C sequestration efficiency (CSE)

The C-yield of pyrolysis is calculated as:

$$C-\text{yield}\,(\%) = \frac{(C_{\text{biochar}} * \text{Yield}_{\text{biochar}})}{C_{\text{feedstock}}} \times 100\% \tag{3}$$

where C-yield is the share of C fixed in the biochar relative to the amount of C in the feedstock (wt%), C_{biochar} is the C content of biochar (g C g^{-1} dry wt biochar), $\text{Yield}_{\text{biochar}}$ is the biochar yield (g dry wt biochar g^{-1} dry wt feedstock) and $C_{\text{feedstock}}$ is the C content of the feedstock (g C g^{-1} dry wt feedstock).

The carbon sequestration efficiency (CSE) of biochar is the product of F_{perm} and C-yield:

$$\text{CSE}\,(\%) = F_{\text{perm}} * C-\text{yield} \tag{4}$$

CSE indicates how much of the initial organic C in the feedstock remains in soil 100 years after the pyrolysed biomass was applied to soil. As both F_{perm} and C-yield relate to H/C_{org}, CSE is also expected to depend on the H/C_{org} of biochar.

3 | RESULTS AND DISCUSSION

3.1 | Model for stability of biochar in soil

Following our selection criteria and using a subset of the data included by Woolf et al. (2021) plus six additional data points of Aubertin et al. (2021), a regression was calculated to estimate F_{perm} as a function of the H/C_{org} molar ratio ($n = 77$) (Figure 1). F_{perm} against H/C_{org} is expressed by a power function ($R^2 = 0.35$; adjusted $R^2 = 0.33$). This model was chosen as it better fits the data compared with a linear model (adjusted $R^2 = 0.20$).

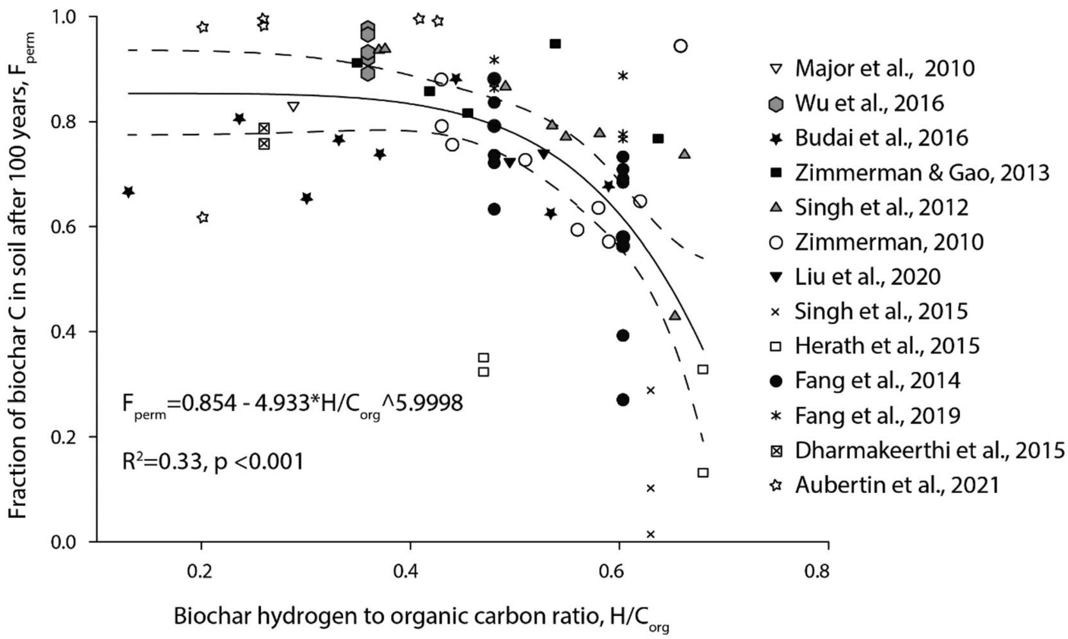

FIGURE 1 Relationship between the molar ratios of biochar hydrogen to organic carbon (H/C_{org}) and calculated fraction of biochar C remaining after 100 years (F_{perm}) for 77 data points from 13 studies with minimum duration of 1 year for a temperature of 14.9°C. Black line shows the best fit, dashed lines the 95% confidence interval of the regression line. Symbols refer to the corresponding references. R^2 refers to the adjusted coefficient of determination.

Also the data set by Woolf et al. (2021), with H/C_{org} ranging up to 1.40, is adequately described by the non-linear power function ($R^2 = 0.34$).

We explicitly only chose the H/C_{org} molar ratio as predictor because this parameter is usually provided for biochars placed on the market and can be routinely measured. In contrast, pyrolysis temperature is often not known and is variable during the pyrolysis process. Furthermore, the H/C_{org} ratio reflects not only HTT but also other pyrolysis parameters controlling biochar properties such as heating time and feedstock type (Almutairi et al., 2023; Ippolito et al., 2020).

The model indicates a moderate decline of F_{perm} with H/C_{org} molar ratios >0.4 and a steep decline of F_{perm} with H/C_{org} molar ratios >0.6. This is reasonable as a greater H/C_{org} molar ratio indicates the presence of non-pyrogenic C or pyrolysis deficiencies (e.g., Schimmelpfennig & Glaser, 2012). It is interesting to note that the variability in the fraction of biochar remaining in soil after 100 years in the range of H/C_{org} values between 0.5 and 0.7 is higher than those with lower H/C_{org} molar ratios. The reason for that could be that exogenous factors (e.g., soil and climatic conditions) have more impact on the decomposition of biochar of lower stability. Fang et al. (2014) showed that the influence of properties of four contrasting soils on biochar-C mineralization was in general greater for biochar produced at lower pyrolysis temperature, hence with lower stability. However, further systematic studies are needed to test whether exogenous factors such as soil properties become more important for less stable biochars. In this context, the greater labile and semilabile fractions of less stable biochars (Rombola et al., 2016) could be important considering that most of the available data of biochar-C mineralization mainly reflects the decomposition of only the most labile biochar fractions (Wang et al., 2016).

We note that the model in Figure 1 is based on a comprehensive, but still limited data set, with a remaining scatter that is introduced by the varying experimental conditions and biochar qualities. The large unexplained variability clearly indicates that a better experimental data base for predicting the long-term fate of biochar in soil is needed. While the effect of different temperatures could be considered using Equation (2), other important rate modifiers for decomposition such as soil moisture, texture or pH could not be explicitly addressed owing to a lack of incubation studies that comply with the criteria set out in the method section.

3.2 | Biochar C-yield

Our results show that both H/C_{org} and C-yield are negatively correlated with pyrolysis temperature (Supplementary Figure S1). Furthermore, our data indicate that there is a linear reduction of C-yield with increasing degree of carbonization expressed as H/C_{org}; for 13 out of 20 feedstocks (Figure 2 and Supplementary Table S2), this relationship is significant ($p < 0.05$). On average, C-yields decline by 1.7% (range 0.3%–4.0%) for a 0.1 step change in H/C_{org}. This is in contrast with previous studies, based on smaller data sets, showing that the declining biochar yield (wt%) with rising HTT above 350°C is mostly compensated by an increase in biochar C content, suggesting that HTT does not considerably affect the C sequestration balance (Lehmann et al., 2006; Mašek et al., 2013). Over the whole H/C_{org} range (0.1–0.7), the C-yield can be reduced by up to 23% (mesquite wood), pointing to a significant loss. The general C-yield is, as expected (Lehmann et al., 2006; Zhao et al., 2013), strongly dependent on the type of feedstock ($p < 0.05$, see intercepts, y0, of linear regression analyses in Supplementary Table S2). It is remarkable that the feedstocks with highest C-yields of >45% are all agricultural residues (hazelnut kernel shell > olive husk > hazelnut shell > sugarcane > corn stover), while the woody feedstocks have overall lower yields of between 38 and 45% (intercepts, y0, of linear regression analyses in Supplementary Table S2). Greater concentrations of lignin but also higher mineral content may be responsible for the relatively higher C-yields of some feedstocks (Raveendran et al., 1995; Lehmann et al., 2006; Zhang et al., 2017; Grafmüller et al., 2022). Olive husk and hazelnut kernel shell for instance contain approximately 20% more lignin than beech and spruce wood (Phyllis2, 2022), thereby leading to considerably high yield (Demirbaş, 2001). A general classification is not straightforward, however, given the still limited data set, as also other factors can influence biochar yield (i.e. heating rate, oxygen availability and particle size of feedstock).

3.3 | Carbon sequestration efficiency (CSE)

The CSE for biochars with $H/C_{org} < 0.6$ ranges from 25% to 50% (Figure 3). The shape of the CSE as a function of

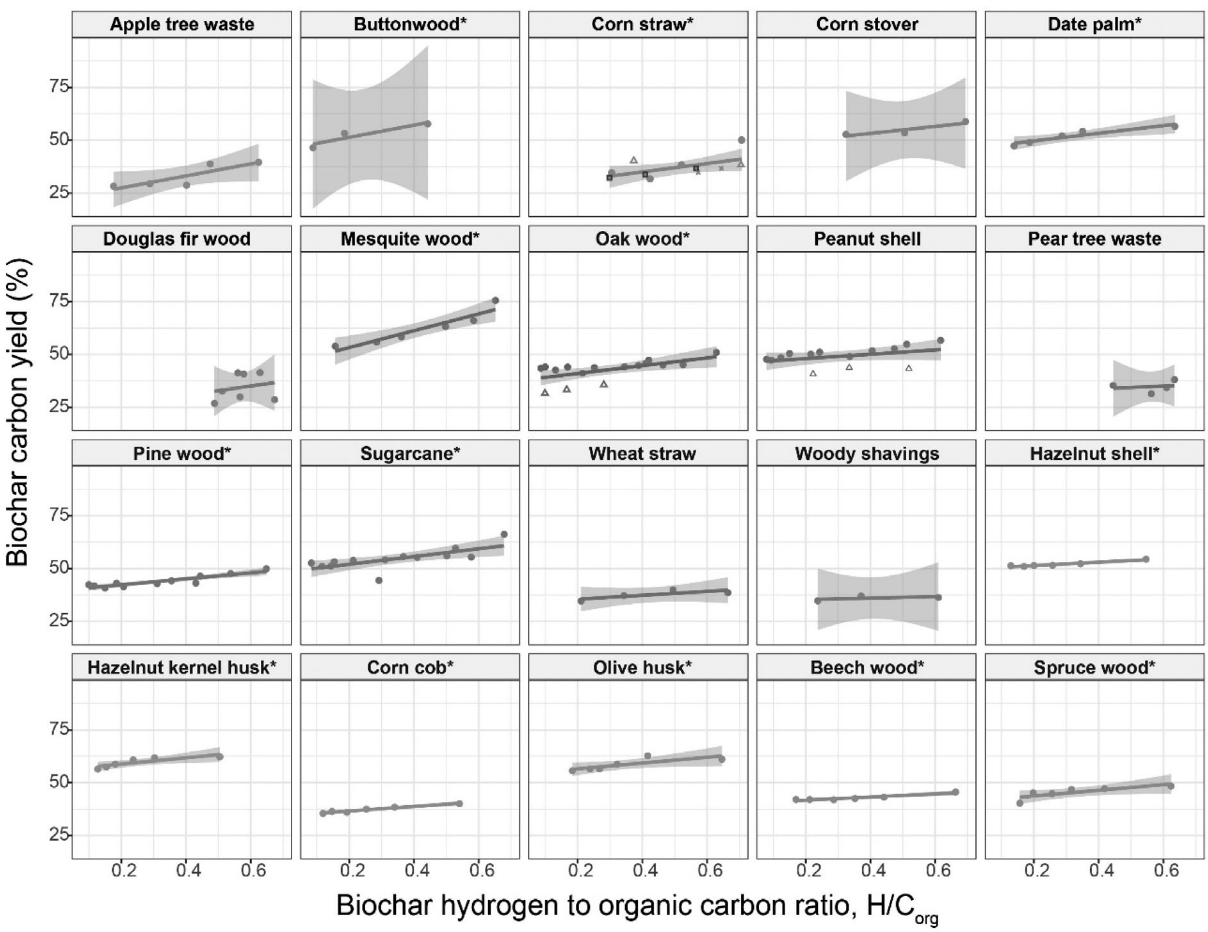

FIGURE 2 Relationship between H/C_{org} of biochars and the C-yield of biochar for different feedstocks. Materials with significant slopes are marked with *. Shaded areas indicate the 95% confidence interval of the regression line, References for these data and regression coefficients are provided in the Supplementary Table S2.

 European Journal of Soil Science

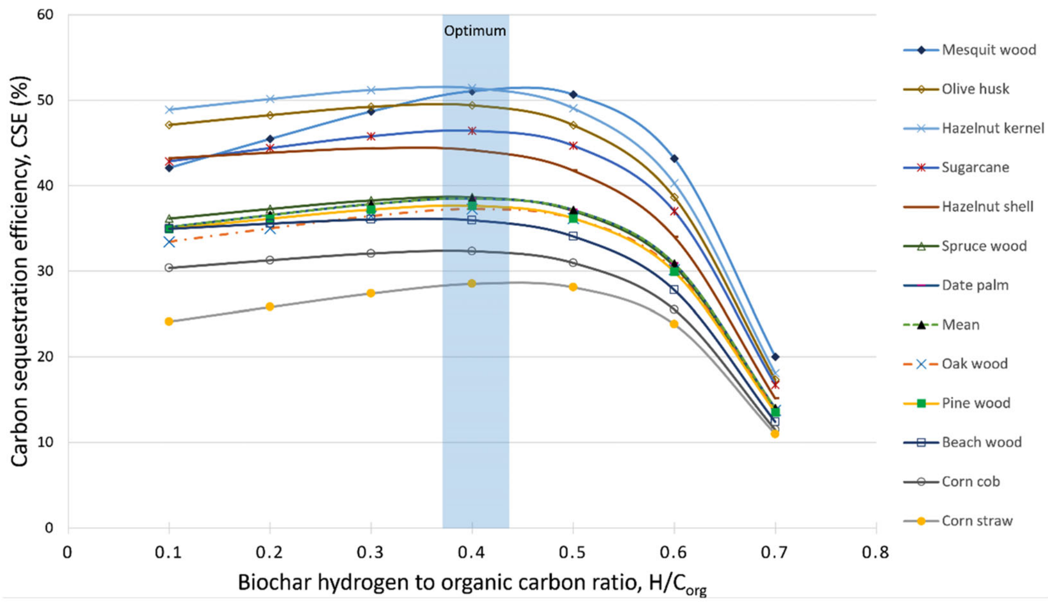

FIGURE 3 Carbon sequestration efficiency (CSE) of biochar applied to soil revealed from combining the biochar stability function in Figure 1 and biochar C-yields during pyrolysis for different feedstocks as provided in Figure 2. Reading example: For a biochar with H/C_{org} molar ratio of 0.4, approximately 50% from the carbon units originally present in the feedstock are left in soil after 100 years in the case of mesquite wood, olive husk and hazelnut kernel.

H/C_{org} is determined by F_{perm}, and the variability in C-yield adds a substantial spread to this picture. The highest efficiencies are achieved for biochars with H/C_{org} of ≤0.5. Some feedstocks such as mesquite wood, olive husk, hazelnut shell and sugarcane are clearly superior to others and achieve higher CSE's. Along the gradient of H/C_{org} ratios from 0.1 to 0.7, CSE is most variable for mesquite wood, because of the steep decrease in C-yield with biochar stability for this material. Almost independently of the feedstock, highest CSE's are most often reached at H/C_{org} ratios of between 0.38 and 0.44, pointing towards a general CSE optimum of 41.4% on average across all studied materials, and with a 95% confidence interval (CI) of 36.9%–45.9%. The H/C_{org} ratios of 0.38–0.44 correspond to pyrolysis temperatures of between 500 and 550°C (see H/C_{org} versus pyrolysis temperature in the Supplementary Figure S1).

Our results suggest that feedstock type, in addition to HTT, controls C-yield and therefore plays a key role for the overall sequestration potential of biochar (Ippolito et al., 2020). Zhao et al. (2013) came to a similar conclusion in a study where biochar stability was estimated by a recalcitrance index determined by dynamic thermal analysis (Harvey et al., 2012). Their study showed that biochar stability was mainly related to HTT, whereas the total potential of C sequestration depended more on feedstock quality.

Feedstocks are often separated into woody and nonwoody materials, and it has been proposed that woody feedstocks should be preferred over non-woody (crop residues and grasses) to optimize soil C sequestration (Hilscher et al., 2009). This relates to the different chemical composition of biomasses (e.g., lignin and ash content) affecting the eventual stability of biochar. For a given set of pyrolysis conditions, woody biochar generally contains a higher proportion of aryl C to alkyl C than biochar from nonwoody biomass, which decreases its susceptibility to microbial decomposition (Hilscher et al., 2009; Singh et al., 2012). However, the separation into woody and nonwoody biomasses may be too simplistic and misleading, because the founding studies mostly compare woody biochar to grass- or manure-based biochar. According to our results, crop-derived feedstocks such as hazelnut shell, olive husk and sugarcane, which are important materials in agricultural practice, have high CSE's resulting from their relatively high C and lignin content. Lignin content of the biomass is probably more relevant as an indicator of biochar C-yield because the C-yield of cellulose and hemicellulose in a pyrolysis temperature range of 400 to 700°C is much smaller than that of lignin (Yang et al., 2007). For the purpose of defining sequestration efficiencies a priori, a separation of feedstock according to its lignin content would therefore be preferable. Because of the variety of methods to describe biomass composition, offering mostly semi-quantitative results (e.g., lignin, hemicellulose and cellulose from proximate analysis), comparison of biomasses from different studies is, however, not straightforward (Lourenço & Pereira, 2018). A reference base describing the composition of the most important biomasses for biochar production using harmonized analytical methods would be desirable for further classification.

To what extent feedstock influences the mineralization of biochar in soils and hence F_{perm} remains an open question. Laboratory studies using thermogravimetric analysis and oxidation resistance to describe stability of biochar indicate that in terms of stability some feedstocks pyrolysed at the same temperature are clearly superior to others (Choudhary et al., 2019; Liu et al., 2020). This might relate to the degree of aromatic condensation in biochars, which is known to be also influenced by feedstock and to control biochar stability beyond aromaticity (McBeath & Smernik, 2009; Wiedemeier et al., 2015). Yet, systematic studies and long-term field or incubation experiments looking specifically at feedstock-derived effects are needed in order to not only estimate biochar C-yield, but also persistence in soil according to feedstock.

3.4 | Practical recommendations and way forward

The production and application of biochar in practice will depend on the availability and cost of the organic materials used as feedstock. Current regulations allow for a wide range of materials, which typically will be sourced from agricultural and forestry residues, considered as by-products from food and timber production, biomass waste, harvest residues or pruning. Integration of biogas production and pyrolysis of dewatered biogas digestates is another pathway of biochar production that might be of interest in the future. Supply chains of feedstocks potentially available for biochar production therefore often include a mix of different materials. In line with our results, the production of biochar with H/C_{org} molar ratios between 0.38 and 0.44, across a wide range of feedstocks, seems to be optimal in terms of C sequestration. This corresponds to HTT in the range of 500–550°C. The results imply that, for achieving the highest benefit in terms of mitigating climate change via biochar C sequestration, pyrolysis temperatures above 600°C are less favourable, at least on a centennial time scale. Furthermore, this is important in terms of energy efficiency. Pyrolysis is an overall exothermic process and pyrolysis gas and oil, the two other products of biomass pyrolysis, can be used to produce electricity and thereby substitute fossil fuels (Lehmann et al., 2021). Increasing HTT requires a higher share of that energy for maintaining the chosen process temperature and therefore reduces the net energy gain of the process. As Patwa et al. (2022) showed, an increase in HTT by 100°C increases the energy consumption by about 20%.

In relation to biochar effects on fluxes of other greenhouse gases from soil, Cayuela et al. (2015) showed that materials with H/C_{org} ratio <0.3 were the most effective to mitigate N_2O emissions. The effect of biochars on reducing N_2O emissions, however, seems to act mainly for the first few years after application to soil whereas long-term effects are uncertain (Borchard et al., 2019; Woolf et al., 2021). In addition, work by Thers et al. (2019) indicated that the climate benefit from C sequestration by biochar in a rape-seed cropping system surpassed the climate benefit of reduced N_2O emission by an order of magnitude.

4 | CONCLUSIONS

Our model of biochar C sequestration based on biochar H/C_{org} complements previous work (Woolf et al., 2021) by including the biochar C-yield into the overall assessment, and by assigning a smaller F_{perm} to more labile biochars. The difference in F_{perm} is mostly owing to the more rigid criteria we set for biochar qualities to be included from a practical viewpoint. We consider this relevant because the quality thresholds set by IBI and EBC are gaining importance for biochar application in practice (EBI, 2022) and strongly influenced the quality criteria for biochar in the most recent EU regulations on fertilizing products (EU, 2019, 2021). The new EU regulation opens European markets to biochars and represents a critical step in the implementation of significant soil C sequestration with biochar, which should be further promoted by the rapid development of C farming markets. Furthermore, combining F_{perm} with C-yield towards an overall C sequestration efficiency provides a step towards a more comprehensive system analysis of biochar application in terms of carbon sink certification (EBC, 2020) and the important question of how to deal with permanence and the longevity of sinks (Leifeld & Keel, 2022; Oldfield et al., 2022). Our approach is also suitable to classify biochar by its stability and with this will help to inform soil C models towards a better representation of this amendment (Keel et al. under revision).

The currently available, reliable data on biochar decomposition used in this study highlight the role of feedstock and pyrolysis temperature in determining F_{perm} and biochar mean residence times as well as C sequestration efficiencies. However, it does not yet allow to disentangle the role and lever of important driving factors (e.g., soil properties and climate). In particular, field experiments that allow to unambiguously trace the fate of biochar in soil and that encompass a wide range of site conditions such as soil pH, texture and mineralogy, as well as land-use and climatic factors need to be established in future studies to reduce the uncertainty in estimating the role of biochar for soil C sequestration in practice.

AUTHOR CONTRIBUTIONS

Leonor Rodrigues: Writing – original draft; conceptualization. **Alice Budai:** Writing – review and editing. **Lars Elsgaard:** Writing – review and editing. **Brieuc Hardy:** Writing – review and editing. **Sonja G. Keel:** Writing – review and editing. **Claudio Mondini:** Writing – review and editing. **César Plaza:** Writing – review and editing. **Jens Leifeld:** Conceptualization; funding acquisition; writing – review and editing; supervision.

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CONFLICT OF INTEREST STATEMENT

The authors report there are no competing interests to declare.

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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SUPPORTING INFORMATION

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