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Biochar

REVIEW

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Biochar's effect on the soil carbon cycle: a rapid review and meta-analysis

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Abstract

Biochar offers opportunities for improving soil carbon (C) sequestration and reducing CO_2 emissions to the atmosphere. It has emerged as a strategy for mitigating climate change and improving the soil carbon cycle (SCC). While previous review studies have primarily investigated the effects of biochar on greenhouse gas (GHG) emissions, a considerable research gap remains regarding its impact on the SCC. The present study aims to bridge this gap by examining the main SCC components: total CO_2 flux, total microbial respiration, and C sequestration. We conducted a global meta-analysis which included 75 studies and 250 observations. The results show an average 11% increase in soil total CO_2 flux from biochar, but the confidence interval (CI) slightly touches the no-effect line (CI [0%, 23%]). Total microbial respiration remains unchanged after the application (10%, CI [− 2%, 23%]). In contrast, soil C sequestration benefits from biochar by 61% (CI [36%, 90%]). Our analysis identified key predictors affecting SCC components: experimental design, continent, biochar application rate, feedstock type, and pyrolysis temperature. Incubation experiments reveal benefits for all SCC components. The Middle East, Europe, and Asia exhibit potential for enhancing C sequestration with biochar. Higher application rates amplify C sequestration and total microbial respiration. Manure biochar enhances total microbial respiration, while woody biochar influences total CO_2 flux. Furthermore, lower pyrolysis temperatures show promise for improving C sequestration and total microbial respiration. In conclusion, while biochar holds promise for C sequestration, its impact on total microbial respiration and total CO_2 flux remains inconclusive.

Highlights

- Meta-analyses revealed the impact of biochar on three key elements (C sequestration, total CO_2 flux, and total microbial respiration) of the soil carbon cycle.
- Biochar increases soil carbon sequestration significantly.
- The effect of biochar wasn't significant for total microbial respiration and total CO_2 flux responses.

Keywords Soil properties, Soil ecosystem services, Soil amendment, Sustainable agriculture, Climate change, Greenhouse gas emissions

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1 Introduction

Recent projections indicate, worryingly, that global temperatures will likely rise by 3.0 degrees Celsius by 2060 (Pörtner et al. 2022). The main driver of this trajectory is rising atmospheric concentrations of greenhouse gases (GHGs), with human activities making a significant contribution, mainly through carbon dioxide (CO_2) emissions (He et al. 2017). Soil is a crucial carbon sink in terrestrial ecosystems and the second-largest carbon store after the ocean (Lefèvre et al. 2017; FAO 2015; Lal 2018). Globally, soils can hold an estimated 1100 gigatons (1 Gt = 1,000,000,000 tons) of organic carbon, exceeding the carbon content of both the atmosphere (750 Gt) and the terrestrial biosphere (560 Gt) (Paustian et al. 2000). Carbon (C) sequestration in the soil is achieved through sustainable agricultural management such as agroforestry, cover crops, and biochar application (Kumar 2017), indicating one of the most cost-effective and environmentally sound strategies to combat global warming (Lal 2004). Soil C sequestration refers to the process of removing CO_2 from the atmosphere and storing it within the soil carbon pool. Carbon is primarily facilitated by plants through photosynthesis and is stored in the soil in the form of soil organic carbon (SOC) (Ontl and Schulte 2012). This highlights the importance of even small changes in the soil C pool that can play a major role in the concentration of CO_2 in the atmosphere (Lal 2004). Over the past 12,000 years, the expansion of agricultural land has led to the release of approximately 110 billion tons of carbon from Earth's topsoil (Sanderman et al. 2017). In 2005, for example, agriculture was estimated to have contributed approximately 6.1 gigatons of CO_2 equivalent per year to global emissions, accounting for approximately 10–12% of total anthropogenic GHG emissions (IPCC 2007). This significant contribution from the agricultural sector not only exacerbates the challenges of climate change but also threatens the long-term sustainability of the agricultural sector (IPCC 2023; Smith et al. 2008). Poor soil management can also impair soil respiration and potentially increase soil CO_2 emissions, impacting the global terrestrial carbon cycle (Ghorbani et al. 2023).

SOC plays a critical role in regulating essential soil ecosystem services, including nutrient availability, water retention, soil stability, and GHG emissions (Davidson and Janssens 2006; Jackson et al. 2017). Enhancing SOC levels by integrating organic materials into soils contributes to better soil carbon cycling through processes such as mineralization and immobilization (Xie et al. 2007; Gogoi et al. 2020). In this context, the potential of biochar as a tool for C sequestration and soil improvement has received attention. Biochar is a sustainable carbon-rich product derived from pyrolyzing biomass under limited oxygen conditions (Lehmann 2007). Pyrolysis involves heating organic materials such as crop residues, wood chips, or agricultural wastes in a controlled environment at varying temperatures (Bekchanova et al. 2021; Wang et al. 2022).

Biochar, with its highly aromatic structure, is a carbon-sequestering agent known for its remarkable stability and resistance to microbial decomposition compared to other organic materials (Wang et al. 2022; Luo et al. 2023). This stability allows biochar to persist in the soil for centuries, far exceeding the residence time of organic carbon from plant residues, which typically lasts from decades to a few hundred years (Hamer et al. 2004; Novak et al. 2010). Consequently, biochar application can significantly delay the return of fixed carbon to the atmosphere (Woolf et al. 2010; Lehmann et al. 2011). Meanwhile, dissolved organic carbon (DOC) affects SOC decomposition by influencing microbial activity, which can either accelerate or slow down SOC breakdown. It also influences microbial communities, soil chemistry, and SOC stability by forming complexes and altering soil conditions. Similarly, biochar's effect on soil organic matter (SOM) mineralization varies; it can either accelerate (positive priming), slow down (negative priming), or have a neutral effect on SOC decomposition (Wang et al. 2022; Rasul et al. 2022; Luo et al. 2023). For instance, one study observed a 15% increase in carbon mineralization shortly after biochar application (Maestrini et al. 2015), while another reported a negative priming effect over six months (Wang et al. 2016). These varying outcomes might be influenced by differences in SOM composition, microbial communities, and nutrient availability (Rasul et al. 2022). In addition, biochar is believed to increase climate mitigation potential by reducing the demand for agricultural fertilizers (Lin et al. 2015). When applied to agricultural soils, biochar alters soil properties and microbial activity, affecting the soil carbon cycle (SCC) and non-CO_2 GHG emissions (Lehmann et al. 2011), improving the soil C content, and creating a more favorable environment for soil microbial respiration (Wang et al. 2022).

However, the effects of biochar application on SCC and GHG emissions show variations and uncertainties, largely due to the diverse biochar materials and the specifics of different soils (Lin et al. 2015). Biochar pyrolyzed at 600 °C or lower can stimulate microbial activity, leading to increased decomposition of organic material and higher CO_2 emissions from agricultural soils (Chan et al. 2008; Hale et al. 2012). On the other hand, biochar pyrolyzed at high temperatures can accumulate several toxic functional groups, leading to lower CO_2 emissions (Nakajima et al. 2007). In recent meta-analyses, incubation (mainly laboratory) experiments showed higher CO_2 release (Shakoor et al. 2021a, b) than field and pot experiments (He et al. 2017). In short-term experiments, such as soil incubation, biochar can boost microbial activity and accelerate the C mineralization rate, leading to higher soil CO_2 flux (Zimmerman et al. 2011). While some studies based on incubation experiments have claimed that biochar has a short-term effect on soil respiration (Lu et al. 2014; Maestrini et al. 2015), others have shown that the effect can last for at least three years (Wang et al. 2022). Biochar application rate and soil texture were also important factors influencing the responses of CO_2 emissions and soil respiration, with different effects in different studies (He et al. 2017; Wang et al. 2022).

To date, meta-analysis studies have focused on the GHG response to biochar application, but have not studied the SCC (He et al. 2017; Shakoor et al. 2021a, b). To address the existing knowledge gap, we conducted a meta-analysis to examine the empirical evidence regarding the impact of biochar on the SCC. We focused on the three main components of the SCC: C sequestration, total microbial respiration, and total CO_2 flux. The following objectives were set for this meta-analysis: (a) to elucidate the underlying effects of biochar application on SCC based on a rapid review; (b) to investigate the effect of different biochar properties (that is, feedstock type, pyrolysis temperature, experimental design, biochar application rate) and soil system attributes (soil texture, pH, and regions of study) on the SCC. This review provides policymakers with clearer insights into the impact of biochar on soil carbon cycles, aiding in the formulation of effective policy recommendations for its use as a soil amendment. The review results also deliver valuable guidance to biochar producers, farmers, and other stakeholders seeking to improve soil conditions by applying biochar.

2 Materials and methods

2.1 Literature search and screening process

To achieve the objectives of this study, we used bibliographic databases such as Web of Science and Scopus to search for peer-reviewed articles. The search keywords were 'biochar' OR 'charcoal' OR 'char' AND 'CO_2', 'CO_2 sequestration', OR 'CO_2 flux OR 'respiration.' These keywords are formulated in line with the research objectives. The search in both databases included all papers published till May 2023. After duplication removal, our search yielded 2039 publications. Our review comprises two screening stages (Additional File 1). At the first screening stage (abstract and title screening) we excluded the articles that were not based on experimental studies and were outside the scope of the review (that is, not related to SCC). We also included papers on biochar produced from biomass through gasification and/or pyrolysis and used in agriculture as a soil amendment. Studies published in any language other than English were subject to exclusion.

In the next stage, full-text screening, we selected peer-reviewed publications using the following criteria: (a) experiments with at least one control and treatment comparison that also measure CO_2 emissions, total microbial respiration and/or C sequestration, only when all other soil management practices are comparable between the treatment and control groups; (b) experiments where the physicochemical characteristics of biochar, including pyrolysis temperature, type of feedstock, carbon content, and pH, are mentioned; (c) experiments where clearly described experimental designs (such as type of experiment and biochar application rate) are listed; (d) experiments where soil management before and after the experiment are stated; (e) experiments where soil physicochemical properties (such as soil texture, pH, bulk density, soil temperature, and moisture) are mentioned; and (f) experiments where given data are related and readable (for example, means and sample size were reported for each treatment and control together with their corresponding SD and/or SE). Studies were excluded if they did not meet the above criteria.

2.1.1 Data management and collection

When the given data were presented in figures, we used Webplotdigitizer to extract the final data (Bekchanova et al. 2021). If the data were not extractable, we excluded them from the data extraction. Each study reported sometimes multiple estimates for the same SCC component. We took all these estimates from the studies and put them in separate rows. Several estimates from one paper might lead to data dependency, which is addressed in the "meta-analysis" section. In addition, the results in different units have been converted to the same units for each SCC component for analysis purposes. Besides, some studies reported biochar rates in other units of measurement (such as μmol m^{-2}, mg kg^{-1}, or μg g^{-1} or in percent), and all were converted to kg ha^{-1} to standardize units of measurement. For example, to convert μmol m^{-2} to kg m^{-2}, we used Eqs. 1 and 2. Similarly, for the conversion of mg kg^{-1} to kg ha^{-1}, we used soil bulk density and soil maximum depth, as outlined in Eq. 3. The corresponding SDs were calculated if studies presented only standard errors in the publication.

$$\frac{\mu\,\text{mol}}{\text{m}^2} = \frac{1}{10^6} \times 10,000\ \text{mol/ha} \quad (1)$$

$$\text{Mass}\left(\frac{\text{kg}}{\text{ha}}\right) = \text{Moles}\left(\frac{\text{mol}}{\text{ha}}\right) \times \textit{Molecular weight}\left(\frac{g}{mol}\right) \times \frac{1}{1000} \quad (2)$$

$$\text{Mass}\left(\frac{\text{kg}}{\text{ha}}\right) = \left(\frac{\textit{Value in mg/kg}}{1000}\right) \times \left(\textit{Bulk density}\left(\frac{g}{cm^3}\right) \times \textit{Depth}\ (m) \times 10000\right) \quad (3)$$

When soil bulk density for calculation was unavailable, we discussed with experts in the field, and we adopted an average soil bulk density of 1.3 g cm^{-3} following their recommendation (Table 1).

2.1.2 Data compilation

Biochar properties: The soil minimum and maximum depth represent the shallowest and deepest soil layers included in experimental studies, respectively. Soil depths in articles varied, so we categorized minimum depth as 0–10 cm and maximum depth as < 5, 5–15, 15–25, 25–35, and > 35 cm based on the given data. Different feedstocks were used to produce biochar: agricultural residual flows, manure and/or its digestate, and woody biomass (Lataf et al. 2022). We have also grouped the pyrolysis temperature into 'low' if the pyrolysis temperature is less than or equal to 400 °C, 'medium' if the temperature is between 400 °C and 600 °C, and 'high' if the temperature is equal to or greater than 600 °C (Zhang et al. 2021).

*Soil status and management: S*oil texture diverged into four groups based on the USDA (the United States Department of Agriculture) classification (USDA 1999), namely, clay, silty, sandy, and loamy soils. Vegetation type also fell into the following categories based on data availability: agricultural land, forest land, grassland, and urban land (Subcommittee 2008; Box and Fujiwara 2013).

To comprehensively analyze the SCC, we collected various measurements and categorized them into three major components of SCC based on data availability, as shown in Table 2. These SCCs provide a reasonable representation of the complexity of the SCC. Total CO_2 flux represents carbon emission to the atmosphere, while total microbial respiration refers to carbon exchange between the soil and the atmosphere. The difference between total CO_2 flux and total microbial respiration is that the former includes all carbon exchange processes between the soil and the atmosphere, such as photosynthesis (Hashimoto et al. 2023; Wang et al. 2020), while the latter specifically refers to releasing CO_2 from the soil due to the utilization of soil organic matter by microbial and root activity (Hashimoto et al. 2023). The total CO_2 flux is measured using techniques such as eddy covariance, chambers, or CO_2 efflux in the soil (Wang et al. 2009). Total microbial respiration is usually assessed with chambers that capture CO_2 emissions or indirectly via measurements of CO_2 efflux in the soil (Rochette and Hutchinson 2005). CO_2 efflux refers to the emission of CO_2 and is specifically used in the context of soil respiration.

C sequestration is a well-known term for soil carbon storage, leading to lower CO_2 emissions. Biochar's effect on SOC was one of the measurements grouped into C sequestration. Biochar does not function in the same way as traditional SOC, but it does contribute positively by providing a stable, long-term carbon source, improving soil structure and aggregation, and creating a habitat for beneficial soil microbes. Our focus was on evaluating the effect of biochar on SOC rather than considering biochar as a component of SOC itself. During data extraction, we ensured that the experimental design and soil sampling methods were correctly implemented to assess biochar's impact on SOC, as well as other measurements grouped under C sequestration.

2.2 Meta-analysis

We calculated the effect size of the SCC components for each combination of biochar (treatment) and no biochar (control) within a study where the only variation between treatments was the presence or absence of biochar. In this review study, we performed individual meta-analyses for each component of SCC, representing three different meta-analyses. All calculations were done using the *metafor* package (Viechtbauer 2010) in *R version 3.3.0* (Team 2012). The effect size was calculated using the following equation:

$$\text{lnRR} = \ln\left(\frac{\overline{X_b}}{\overline{X_{nb}}}\right) \quad (4)$$

Table 1 Biochar, soil management, and experiment data included as covariates to analyze the variability of biochar effects on SCC components (without outliers)

Category and parameter	Factor levels or range	Number of observations
Study region		
Continent	Asia	148
	Europe	29
	Middle east	18
	North America	32
	Oceania	3
Experimental condition		
Experimental design	Incubation	112
	Greenhouse	16
	Field	102
Experimental duration (days)	< 100	76
	100–300	90
	300–500	32
	500–700	26
	700 <	6
Biochar application rate (t ha^{-1})	< 10	61
	10–30	82
	30–50	41
	50 <	38
Biochar with fertilizer	With fertilizer	28
	Without fertilizer	7
Fertilizer application rate (kg ha^{-1})	> 30	0
	30–120	8
	120–250	10
	250 <	2
Biochar properties		
Feedstock types	Agricultural residue	99
	Manure | digestate	13
	Woody	118
Pyrolysis temperature (°C)	High	40
	Medium	169
	Low	21
Biochar C content (g kg^{-1})	200–400	10
	400–600	99
	600–800	81
	800–1000	16
Soil status and management		
Soil texture	Clay soil	29
	Loamy soil	45
	Sandy soil	102
	Silty soil	54
Soil minimum depth (cm)	0–10	2
Soil maximum depth (cm)	< 5	11
	5–15	95
	15–25	116
	25–35	5
	35 <	3

Table 1 (continued)

Category and parameter	Factor levels or range	Number of observations
Soil pH	4–6	39
	6–8	89
	8–10	80
Soil moisture (%)	< 30	86
	30–50	19
	50–70	76
	70 <	15
Soil temperature (°C)	< 5	8
	5–15	50
	15–25	145
	25 <	22
Irrigation applied	Irrigated	132
	Not irrigated	6
Tillage applied	Tilled	27
	Not tilled	12
Vegetation type	Agricultural soil	210
	Forest soil	5
	Grassland	7
	Urban soil	4

Table 2 Grouped major SCC components relevant to the carbon cycle

Grouped (SCCs)	Extracted measurements
Total CO_2 flux & emission	Cumulative CO_2 emission, Cumulative CO_2 flux, CO_2 production, CO_2 emission, CO_2 flux
Total microbial respiration	Heterotrophic respiration, Soil respiration, Cumulative soil respiration, CO_2 efflux, Cumulative CO_2 efflux
C sequestration	Soil organic carbon, Carbon storage, Total organic carbon, C sequestration

where lnRR is the natural log of the response ratio, $\overline{X_b}$ is the mean value for biochar treatment and $\overline{X_{nb}}$ is the mean values for control. The biochar treatment is considered to have no effect when the $\ln RR = 1$, a positive effect when $\ln RR > 1$, and a negative effect when $\ln RR < 1$. The variation in the number of observations across studies is attributed to the inclusion of diverse management factors, such as tillage, irrigation, and feedstock type, leading to differences in experimental designs. When different levels of management were assessed, and the only distinction was the presence of biochar, they were treated as individual observations in our analysis.

Including multiple effect sizes from the same study introduces a dependency between effect sizes. This dependency among effect sizes challenges the traditional assumption of independence in univariate meta-analyses (Rosenthal and Rubin 1986). We employed the rma.mv function available in the metaphor package, which is suggested for a multivariate approach (Viechtbauer 2010). The meta-analytic model with a three-level structure accounts for three distinct levels of variance: the sample variance of individual effect sizes, the variance between effect sizes within the same study, and the variance between different studies (Assink and Wibbelink 2016). We used the *ANOVA function* in *R* to compare a three-level model with a two-level one, presenting that the three-level model fits our data better. The model is based on limited maximum probability (REML) because it gives unbiased estimates of the variance parameters (Viechtbauer 2010). We further clustered standard errors at the level of primary studies to explain the dependence due to multiple observations from the same study using robust variance estimation (Harrer et al. 2021; Pustejovsky and Tipton 2022). The inverse of the sampling variance was used to weigh individual effect sizes, which has been suggested to account for differences in precision between studies (Hedges and Olkin 2014; Philibert et al. 2012).

Variance data were often not reported or were challenging to extract from figures due to overlapping error bars. Instead of excluding these publications from the analysis, which may introduce bias, we employed the method that Shackelford et al. (2019) described for estimating the standard deviation (USDA) or standard error (Shackelford et al.). This method involved calculating the z-score from reported p-values (e.g., z = 1.96 for a two-sided test when $p = 0.05$) to derive the necessary variance data for the meta-analysis.

To assess publication bias, we employed funnel plots along with PET (precision-effect test) and PEESE (precision-effect estimate with standard error) tests, which are recommended methods for ecological studies (Nakagawa et al. 2022; Stanley and Doucouliagos 2012). Publication bias arises when non-significant or small effect-size studies remain unpublished, leading to a non-normal distribution of LnRR (Egger et al. 1997). Publication bias can create asymmetry in the funnel plot, while studies without bias are symmetrically distributed around the pooled effect size (Harrer et al. 2021). PET-PEESE addresses the effects of small studies, which are potential indicators of publication bias. The PET method is based on a regression model where the square root of the inverse of effective sample size ($\sqrt{1/\ \widetilde{n_i}}$) of the study's effect size (Nakagawa et al. 2022) is regressed as follows:

$$y_i = \beta_0 + \beta_1(\sqrt{1/\ \widetilde{n_i}})_i + s_{(2)ij} + u_{(3)j} + \varepsilon_{ij} \qquad (5)$$

where β_0 is the overall estimate (or meta-analytic mean), the term ij is an effect size where i nested in cluster j, $s_{(2)ij}$ is within-cluster heterogeneity on Level 2, $u_{(3)j}$ is between-cluster heterogeneity on Level 3, and ε_{ij} is the corresponding sampling error (Assink and Wibbelink 2016). PEESE is similarly regressed as PET. The only difference is that, instead of ($\sqrt{1/\ \widetilde{n_i}}$), the variance (square of ($1/\ \widetilde{n_i}$) (Nakagawa et al. 2022) is used as the predictor (Nakagawa et al. 2022). Small studies are more prone to reporting highly overestimated effects, which can introduce bias. In cases where no evidence of publication bias is found, a multilevel model with random effects (ML-REML) is a suitable choice for analysis, as it provides unbiased estimates in the absence of bias (Harrer et al. 2021).

To examine the impact that the effect modifiers listed in Table 1 have on the overall effect, we used randomized LASSO (least absolute shrinkage and selection operator), a cutting-edge model selection technique for regression analysis with high-dimensional data. LASSO identifies significant predictors by shrinking some coefficients to zero, enhancing model interpretability, and preventing overfitting (Meinshausen and Bühlmann 2010). Our study applied randomized LASSO to address variable selection problems, quantifying the variable importance for each SCC. To assess variable importance, we ran the model for five different sizes (1–5 regressors) per SCC, calculating the selection probabilities for each predictor (effect modifiers). Higher probabilities indicated robust predictors for the effect of biochar on SCCs, while lower probabilities suggested weaker effects. Consistently high probabilities signified strong predictors, while zero-percent probability indicated unimportant predictors. To tackle publication bias, we incorporated the square root of the effective sample size in the LASSO model, using the measure of precision as an indicator of publication bias. We also used individual moderator analysis (IMA) to assess the significance of effect modifiers on the overall effect.

To identify potential outliers, we employed a standard boxplot analysis. We assessed each data point by calculating the first and third quartiles and the interquartile range (IQR) of 1/SE. Any data point falling below the first quartile or exceeding the third quartile by a magnitude of 3 times the IQR was classified as an outlier. A sensitivity analysis was conducted to evaluate the impact of assumed values on the variances of effect sizes. In most cases, variances are calculated from treatment and control means' SD or SE. However, most studies did not report SD and SE, so we estimated the variances using the reported p-values instead (Shackelford et al. 2019). This approach enabled us to account for the missing data and ensure robustness in our analysis. The outcomes of sensitivity analyses are provided in the Additional File for reference.

3 Review findings

3.1 General overview of data

According to the observations, most studies were conducted in China (with 30 studies), followed by Germany and the US; Italy also contributed significantly (Fig. 1). Moreover, from 2014, we noticed a remarkable increase in publications (Fig. 2).

The dataset contained varying observations and unique papers for three major components of SCC: total CO_2 flux, total microbial respiration, and C sequestration. In particular, the total CO_2 flux had the highest number of observations (95 from 31 papers), followed by the total microbial respiration with 89 observations from 29 papers, and C sequestration with 46 observations from 15 papers. These numbers provide valuable insights into the availability of data and the frequency of research on each component of SCC.

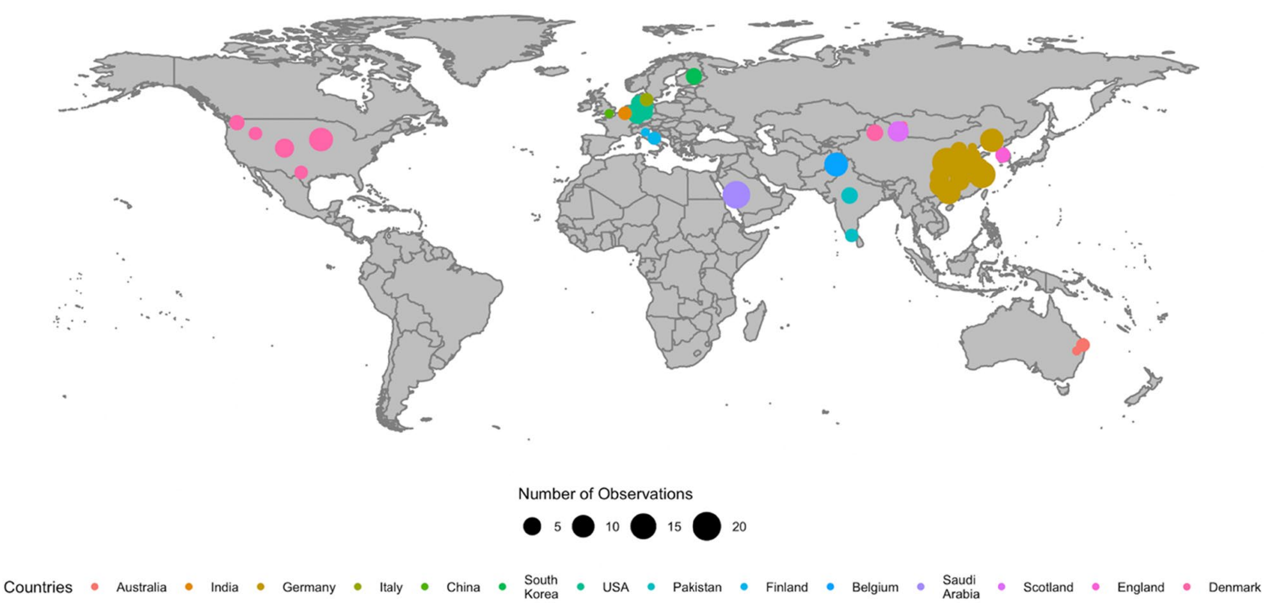

Fig. 1 Number of observations by countries

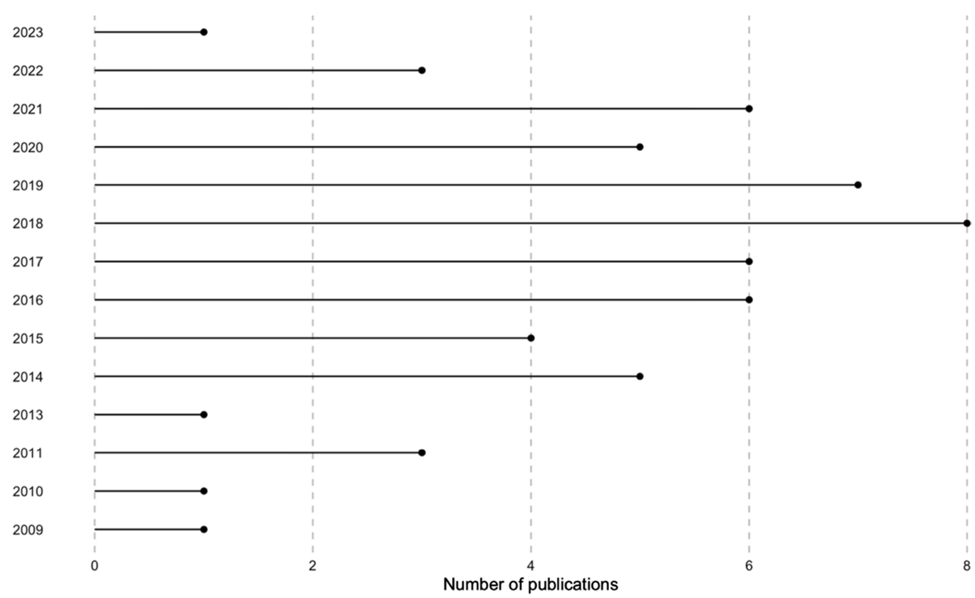

Fig. 2 Distribution of papers over the years

3.2 The overall effect of biochar on the SCC

Based on Fig. 3 it can be seen that the results of three separate meta-analyses, each representing different components of SCC. 9% of the observations utilized in the meta-analyses were identified as outliers based on the predetermined criteria outlined in the "Meta-analysis" section (Additional File). We found that the mean effect sizes remained consistent after conducting sensitivity analyses by excluding the identified outliers. There were no significant shifts from positive to negative, significant to non-significant, or vice versa for any of the SCCs examined in this study (Additional File). Consequently, the results are robust to the removal of outliers, and we present the outcomes without outliers for clarity and accuracy.

The PET-PEESE models suggest that publication bias is negligible in the literature, and no correction for publication bias was required for any SCC. This finding aligns

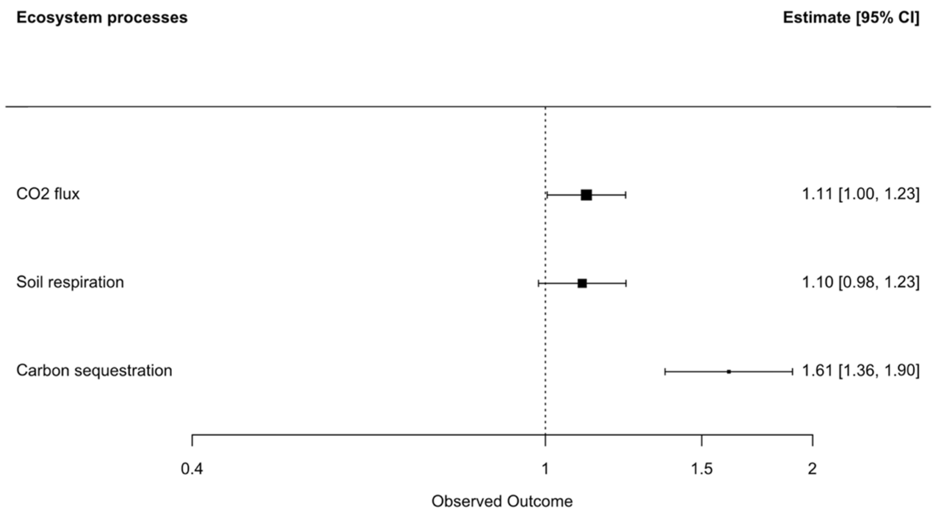

Fig. 3 The response of SCCs to biochar application: estimated meta-averages corrected for publication bias (PET & PEESE model). An effect is significant ($P < 0.05$) if its 95% confidence interval (CI) does not include 1. Confidence intervals are not symmetrical around the effect sizes because they were back-transformed from the log response ratio

with the observation that the estimated meta-averages and confidence intervals remain unchanged for the models, regardless of whether they include or exclude adjustment for publication bias (Additional File). According to the results, soil total CO_2 flux appears to benefit from biochar application, showing an 11% increase. However, the confidence interval (CI) slightly crosses the no-effect line (CI [00%, 23%]), indicating that the effect of biochar on total CO_2 flux is not statistically significant between the treatment and control. Similarly, total microbial respiration did not show a significant effect after biochar application; even though Fig. 3 indicates a 10% increase, the CI [− 2%, 23%] clearly intersects the no-effect line. On the other hand, soil C sequestration greatly benefits from biochar application, with a substantial 61% (CI [36%, 90%]) increase. This implies that biochar contributes to the reduction of CO_2 emissions.

3.3 The influence of effect modifiers on the overall response of SCCs

Table 3 summarizes our findings from both LASSO and IMA analyses, offering valuable insights into the most important predictors and their impact on the response of SCC components. The sections below delve into the key predictors and their respective effects, shedding light on the critical factors influencing soil carbon cycling.

3.3.1 The influence of effect modifiers on the overall response of total CO2 flux

Based on the LASSO results, the experimental duration was found to be an important predictor with a negative influence on the total CO_2 flux response (Fig. 4a). The results from IMA indicated that a more pronounced effect of 17% (CI [2%, 35%]) on the total CO_2 flux response was observed in the experimental durations of 100–300 days (Table 4). The LASSO analysis highlighted feedstock types, especially agricultural residues and woody biomass, as important predictors. Agricultural residue had a negative impact, while woody biomass had a positive impact on the total CO_2 flux response. IMA results displayed in Table 4 that woody biomass biochar increased the CO_2 flux response by 19% (CI [5%, 35%]), while agricultural residue had no significant effect (CI [− 6%, 20%]), suggesting that woody biomass contributed more to the total CO_2 flux than other types of feedstock.

LASSO also identified sandy soils as an important predictor positively impacting total CO_2 flux. The IMA results confirmed a significant effect of sandy soils on the total CO_2 flux response, increasing it by 33% (CI [3%, 72%]) (Table 4). Both LASSO and IMA agreed on the positive effect of incubation experiments on soil total CO_2 flux (Table 4), suggesting that it significantly increased (23%, CI [7%, 42%]) the total CO_2 flux response. IMA results revealed the significant impact of the biochar application rate on the total CO_2 flux response, particularly with the application rates of 10–30 (14%, CI [1%, 28%]) and 30–50 (24%, CI [9%, 40%]), showing the increase in the response (Table 4). The importance of other predictors and their interaction are detailed in the Additional File.

3.3.2 The influence of effect modifiers on the overall response of C sequestration

Based on the LASSO analysis, experimental designs, particularly incubation and field designs, emerged as key

Table 3 The results of IMA and LASSO for each SCCs

	Total CO_2 flux		C sequestration		Total microbial respiration	
	IMA	LASSO	IMA	LASSO	IMA	LASSO
Study location and climate						
Continent			*	x		x
Annual temperature						
Annual precipitation						
Experimental condition						
Experimental design		x	***	x	*	x
Experimental duration		x	*			
Biochar application rate	*		**			x
Biochar with fertilizer						
Fertilizer application rate			*		*	
Biochar properties						
Feedstock types		x			***	
Pyrolysis temperature				x	*	
Biochar C content					**	
Soil status						
Soil texture		x				
Soil pH						
Soil minimum depth						
Soil maximum depth						
Soil moisture						
Soil temperature			*			
Irrigation application						
Tillage application						

The consistent direction of the effect was observed across the LASSO analysis, and the sign of the coefficients for the selected variables was determined using an ordinary least squares regression (Kang et al. 2013). LASSO analysis identified important predictors for the response of SCC, denoted by "x."

The symbols are given based on the significance level of IMA: ***$p < 0.001$

**$p < 0.01$

*$p < 0.05$

predictors for the response (Fig. 4b). Incubation experiments had a more robust and positive effect, whereas field experiments showed a less robust and negative effect on the response. The IMA results further confirmed the significant impact of experimental design, as depicted in Table 4. The incubation experiment showed a significant 165% increase in C sequestration (CI [129%, 207%]), while the field experiment showed a 33% increase (CI [24%, 42%]), which contrasts with the findings from the LASSO analysis. Despite not being selected by LASSO, the IMA results revealed that greenhouse experiments also had a significant impact, leading to a 69% increase in C sequestration (CI [34%, 113%]). However, the number of observations is not evenly distributed, so they should be interpreted with caution.

According to the LASSO analysis, low pyrolysis temperature was identified as an essential predictor that positively affects the C sequestration response. However, the IMA results indicated that pyrolysis temperature was generally not statistically significant (Table 3). Nonetheless, Table 4 demonstrates that low pyrolysis temperature did show a higher effect (354%) with very low precision, likely due to a limited number of observations. This highlights the need for careful interpretation of the results. The Middle East and Asia were identified as important predictors with contrasting effects on C sequestration (Fig. 4b). The Middle East showed a positive effect, while Asia exhibited a negative impact. The significance of this predictor was further confirmed by IMA, where biochar increased C sequestration in the Middle East by 143% (CI [34%, 342%]), albeit with low precision due to limited observations, and by 42% (CI [21%, 66%]) in Asia (Table 4). These findings highlight the potential regional variations in the impact of biochar application on C sequestration. Although LASSO did not select the experimental duration and biochar application rate as significant predictors, the IMA results highlighted their importance for the response. In particular, the lowest

Table 4 Summary of most important predictors selected by LASSO and IMA: "lb" – lower bound; "ub" – upper bound

Predictor	Categories of a predictor	IMA (*P* value)	Effect in %	CI [lb; ub] in %	Number of observations
Total CO_2 flux					
Experimental duration (days)	< 100	$P = 0.6034$	17	[− 4; 44]	25
	100–300		17	[2; 35]	46
	300–500		3	[− 23; 37]	12
	500–700		5	[− 14; 29]	12
Type of feedstock	Woody	$P = 0.2394$	19	[5; 35]	46
	Manure|digestate		26	[− 15; 87]	7
	Agricultural residue		7	[− 6; 20]	42
Soil texture	Clay soil	$P = 0.2737$	23	[− 18; 84]	5
	Sandy soil		33	[3; 72]	20
	Loamy soil		15	[− 2; 34]	39
	Silty soil		− 1	[− 17; 19]	31
Experimental condition	Field	$P = 0.2163$	9	[− 4; 23]	41
	Greenhouse		− 5	[− 36; 41]	5
	Incubation		23	[7; 42]	49
Biochar application rate (t ha^{-1})	< 10	$P = 0.0363$	4	[− 9; 18]	30
	10–30		14	[1; 28]	32
	30–50		24	[9; 40]	21
	50 <		14	[− 4; 35]	12
Carbon sequestration					
Experimental condition	Field	$P < 0.0001$	33	[24; 42]	25
	Greenhouse		69	[34; 113]	3
	Incubation		165	[129; 207]	18
Experimental continent	Asia	$P = 0.0183$	42	[21; 66]	32
	Europe		120	[62; 198]	5
	Middle east		143	[34; 342]	9
Pyrolysis temperature	High	$P = 0.1757$	76	[22; 153]	7
	Low		354	[45; 1419]	3
	Medium		56	[30; 86]	36
Experimental duration (days)	< 100	$P = 0.0214$	156	[85; 254]	16
	100–300		35	[9; 66]	18
	300–500		39	[4; 87]	5
	500–700		85	[30; 161]	5
	700 <		46	[− 11; 141]	2
Biochar application rate (t ha^{-1})	< 10	$P = 0.0004$	24	[00; 54]	9
	10–30		55	[29; 87]	17
	30–50		74	[43; 112]	10
	50 <		202	[87; 388]	7
Soil temperature (in °C)	< 5	$P = 0.0363$	28	[− 25; 120]	2
	5–15		31	[− 9; 90]	5
	15–25		55	[30; 84]	29
	25 <		178	[84; 320]	10
Total microbial respiration					
Experimental condition	Field	$P = 0.0344$	-2	[− 19; 18]	38
	Greenhouse		-8	[− 40; 39]	6
	Incubation		39	[12; 72]	45

Table 4 (continued)

Predictor	Categories of a predictor	IMA (*P* value)	Effect in %	CI [lb; ub] in %	Number of observations
Biochar application rate (t ha^{-1})	< 10	*P* = 0.2302	3	[− 16; 26]	22
	10–30		6	[− 11; 27]	38
	30–50		18	[− 13; 59]	13
	50 <		34	[5; 72]	19
Type of feedstock	Agricultural residue	*P* < 0.0001	6	[− 10; 23]	38
	Manure|digestate		472	[208; 906]	6
	Woody		5	[− 9; 22]	45
Experimental continent	Asia	*P* = 0.7340	5	[− 14; 27]	56
	Europe		23	[− 9; 67]	18
	Middle east		12	[− 45; 126]	9
	North America		32	[− 21; 118]	14
Pyrolysis temperature	High	*P* = 0.0251	− 6	[− 28; 22]	16
	Low		46	[11; 91]	16
	Medium		9	[− 9; 31]	57
Biochar C content (g kg^{-1})	200–400	*P* = 0.0008	-3	[− 54; 105]	3
	400–600		50	[22; 84]	41
	600–800		− 12	[− 27; 7]	33
	800–1000		17	[− 32; 101]	7

experimental duration (156%, CI [85%, 254%]) showed the most significant effect compared to the longer duration (Table 4). In addition, higher application rates had a more pronounced impact on the response than lower application rates (Table 4). Soil temperature was also identified as a significant predictor by IMA, and the results indicated that C sequestration was increased only at higher soil temperatures (Table 4).

3.3.3 The influence of effect modifiers on the overall response of total microbial respiration

LASSO identified the incubation design as the most robust predictor positively influencing total microbial respiration response. At the same time, the greenhouse experiment was selected with a less robust and negative effect. IMA results validated these findings, showing an increased total microbial respiration response in the incubation experiment (39%, CI [12%, 72%]), but no effect in the greenhouse experiment (Table 4). Additionally, LASSO highlighted the biochar application rate as a key predictor with a positive effect; IMA revealed that the highest application rate had a higher impact on the response (34%, CI [5%, 72%]) (Table 4). LASSO results were intriguing as they suggested North America's positive effect and Asia's negative effect on total microbial respiration response. However, IMA did not find any significant effect of any continent on this response (Table 4).

In addition, according to IMA, feedstock types, such as manure and its digestate, appeared as the significant predictor for the total microbial respiration response (Table 4). This finding is confirmed in Table 4, showing a significant increase in the response under biochar from manure and digestate application (472%, CI [208%, 906%]), albeit with low precision due to limited observations. Moreover, in our analysis, IMA highlighted the significance of biochar carbon content (Table 4) and pyrolysis temperature (Table 4) as predictors. Specifically, biochar with a carbon content of 400–600 g kg^{-1} led to a 50% increase in total microbial respiration (CI [22%, 84%]), and lower pyrolysis temperatures were also significantly influential, resulting in a 46% increase (CI [11%, 91%]) in the response.

(See figure on next page.)

Fig. 4 Results of randomized LASSO on the key predictors **a** in the total CO_2 flux response (The variables chosen in at least one out of five LASSO models); **b** in the C sequestration response; **c** in the total microbial respiration response

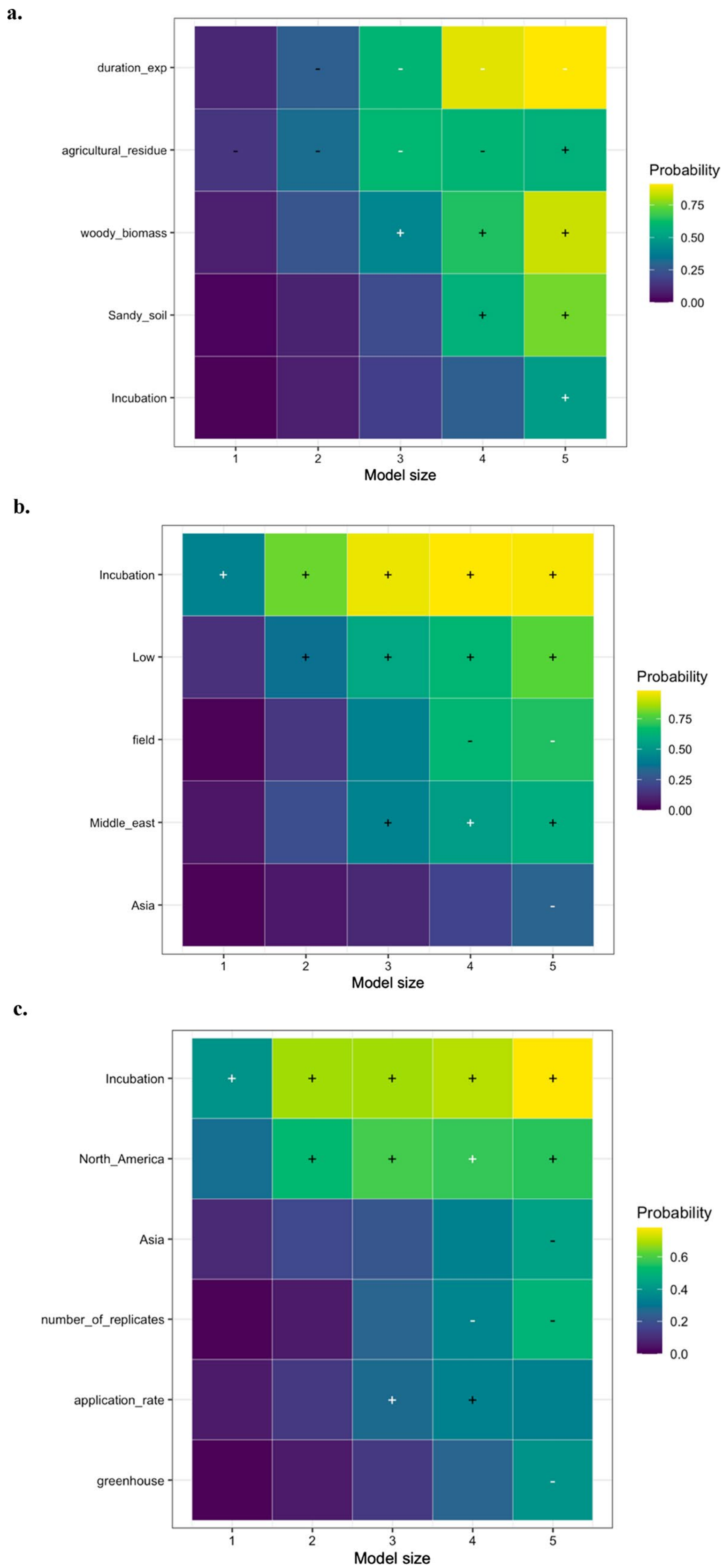

Fig. 4 (See legend on previous page.)

4 Discussion

Our meta-analysis revealed substantial variability in the response of SCC components in biochar-amended agricultural soils. This variability can be explained by several key factors, including diverse biochar physicochemical attributes (explained, for instance, by feedstock type and pyrolysis temperature), variations in soil characteristics (pH, texture, moisture, temperature), differing experimental conditions (greenhouse, incubation, field), as well as variations in biochar application rates (Fidel et al. 2019; Shakoor, Shakoor et al. 2021a, b; Lévesque et al. 2020; Tarin et al. 2021). These detailed factors contribute to the complex and diverse outcomes observed in SCC responses across various studies, as supported by existing literature (He et al. 2017; Shakoor et al. 2021a, b).

4.1 Biochar effects on total CO_2 flux

On average, our meta-analysis showed a trend that biochar application increased soil total CO_2 fluxes but it was not statistically significant between the control and treatment, implying no effect (Fig. 3). Based on our findings, variations in total CO_2 flux response due to biochar application can be attributed to several key factors including biochar application rates (ranging from 10 to 30 t ha^{-1} and 30–50 t ha^{-1}), experimental conditions (such as incubation), the soil texture and the type of feedstock used (particularly woody biomass). On the other hand, other similar studies stated that the increase in soil total CO_2 fluxes following biochar application is often attributed to higher labile C mineralization and/or the release of inorganic carbon from biochar (Jones et al. 2011; Zimmerman et al. 2011). Kimetu and Lehmann (2010) reported that the increased CO_2 fluxes in the soil may be linked to the relatively high SOC content in the soil to which biochar has been applied.

In our study, the application of wood-derived biochar resulted in increased total CO_2 flux, whereas the use of manure-derived and agricultural residue biochar did not show a significant effect on total CO_2 flux (Table 4). Wood-derived biochar, known for its high carbon content (Ginebra et al. 2022), can lead to faster soil C mineralization (Liu et al. 2016a), which might ultimately result in higher total CO_2 flux. A recent meta-study found that manure-derived biochar can also act as a CO_2 sink, reducing CO_2 emissions into the atmosphere by stabilizing carbon in the soil (He et al. 2017). Another meta-study showed contrasting results, indicating that manure-derived biochar increases CO_2 flux due to its quick decomposition facilitated by soil microbial nitrogen availability (Liu et al. 2016a).

The impact of biochar amendment on soil total CO_2 fluxes also varied depending on the experimental designs used. According to the results we obtained, significant positive responses of total CO_2 flux were observed in incubation, whereas greenhouse and field studies showed a non-significant response (Table 4). These findings agree with the experimental duration, where a positive total CO_2 flux response was detected in a short experimental period, while the response was insignificant in longer experimental durations (Table 4). In short-duration experiments like soil incubation, the bio-accessible C fraction and increased surface area of biochar particles can potentially create a niche that supports microbial activity (Chia et al. 2014; Pokharel et al. 2020). This, in turn, accelerates the rate of C mineralization, leading to a higher soil CO_2 flux (Zimmerman et al. 2011). Consistent with findings from another meta-analysis (Liu et al. 2016a), biochar amendment significantly increased CO_2 fluxes in coarse soils, such as sandy soils, while non-significant effects were observed in fine-textured soils (Table 4). This might be because enhanced soil aeration and increased contact between biochar and soil particles in coarse soils likely contribute to the accelerated rate of soil organic C decomposition facilitated by sufficient oxygen supply (Rogovska et al. 2011; Stewart et al. 2013). IMA results showed that biochar application rate significantly predicts total CO_2 flux response, with notable positive effects observed at applications of 10–30 and 30–50 t ha^{-1}. The increase in total CO_2 flux at these specific rates can be attributed to the enhanced mineralization of soil organic carbon (Jones et al. 2011).

4.2 Biochar effects on C sequestration

Biochar application significantly increased soil C sequestration (Fig. 3), reducing atmospheric CO_2 concentration. Biochar, with its high proportion of recalcitrant carbon, is considered a promising method for sequestering soil carbon and reducing GHG emissions (Schmidt et al. 2002). Applying high C: N biochar can lead to the immobilization of microbial nitrogen in the soil, which leads to reduced microbial activities and, subsequently, to an increase in SOC and C sequestration (Kirkby et al. 2014). The response of C sequestration increased in all experimental designs (Table 4). Compared with field and greenhouse experiments, biochar performed better at improving the response in incubation experiments. Previous studies (Fidel et al. 2019; Wang et al. 2019) have highlighted the differences between field and greenhouse studies, mainly attributed to non-existing environmental factors in controlled settings. In the incubation or greenhouse experiments, conditions are nearly ideal with minimal disturbances, unlike the dynamic and complex conditions found in field environments. Under field conditions, various dissipation pathways like wind and water erosion, leaching, and bioturbation also come into play, adding to the system's complexity (Gross et al. 2021).

Moreover, factors such as crop growth and soil tillage play a significant role in soil structure, closely linked to the stabilization of SOC (Guo et al. 2020), making them crucial influencing factors for the potential C sequestration of soil amendments (Xu et al. 2019).

Overall, biochar addition resulted in an increase in C sequestration response across all experimental continents. The most pronounced effect was observed in the Middle East, followed by Europe and Asia (Table 4), which could be explained by variations in observations between different experimental continents. The findings regarding experimental duration reveal a compelling trend in the response of C sequestration to biochar application. Notably, the response was pronounced during shorter experimental durations as opposed to longer ones. This phenomenon is likely attributed to the immediate application and incorporation of freshly produced biochar, which is rich in carbon content, into the soil matrix. The introduction of this new biochar induces a robust microbial response, accelerating the conversion of labile carbon fractions—a phenomenon commonly referred to as a positive priming effect (Gross et al. 2021).

Our findings show that biochar pyrolyzed at low temperatures (≤400 °C) has a significantly higher positive effect on C sequestration compared to medium (400–600 °C) and high (≥ 600 °C) pyrolysis temperatures (Table 4). This might be because biochar produced under low-pyrolysis conditions may have a higher carbon content (Tomczyk et al. 2020) and a recalcitrant nature, allowing it to persist in the soil for extended periods without significant carbon loss (Weng et al. 2022); however, this characteristic varies depending on the feedstock used (Gross et al. 2021). This long-term stability ensures that the sequestered carbon remains stored in the soil, making biochar a reliable and effective solution for long-term C sequestration (Li and Tasnady 2023). However, the number of observations for the effect of biochar, pyrolyzed at low temperatures, on C sequestration was much lower than that of biochar pyrolyzed at high and medium temperatures. Consequently, further studies are warranted to comprehensively understand the impact of biochar pyrolyzed at low temperatures on C sequestration. Our results showed that the higher the biochar application rate, the higher the C sequestration response. A higher biochar application rate increases the presence of biochar particles in the soil. This could stimulate the formation of stable soil aggregates, protecting organic matter from rapid decomposition. Our analyses observed that higher soil temperatures create optimal conditions for enhancing C sequestration. This may align with the phenomenon attributed to the biochar's capacity to decelerate carbon decomposition processes, resulting in the sequestration of a greater amount of carbon (Yang et al. 2020). These findings suggest that careful consideration of predictors is critical for optimizing the effectiveness of biochar in influencing C sequestration.

4.3 Biochar effects on total microbial respiration

Based on our review analysis, biochar did not have a significant effect on total microbial respiration (Fig. 3). There are several potential reasons for this, including lower biomass production leading to reduced mineralization of plant litter, lower microbial population in biochar-amended soils, or reduced root respiration (Major et al. 2010). The predictive analysis revealed that biochar properties and experimental designs significantly influenced the total microbial respiration response to biochar application. Incubation experimental design showed a higher response, while greenhouse and field experiments exhibited non-significant effects (Table 4). In incubation experiments, the fine grinding of soils and biochars increased accessibility to soil microorganisms, leading to higher total microbial respiration rates (Luo et al. 2011; Jones et al. 2011; Troy et al. 2013). Furthermore, the controlled and favorable environment in incubation experiments, with consistent temperature and soil moisture, could stimulate soil microbes' growth and active response to the accessible exotic carbon present in biochar (Liu et al. 2016b). However, in field conditions, organic substances might be physically protected in macro-aggregates or tightly bound to soil minerals, limiting their availability to soil microbes (Liang et al. 2010).

The tuning of increase in total microbial respiration with a higher biochar application rate in our analysis may be due to the increase in reactive organic carbon concentration enhancing soil microbial activity (Chen et al. 2018) (Table 4). Consistent with the hypothesis that biochars with increased labile carbon content, such as manure-derived biochars and higher carbon biochars, could improve total microbial respiration by providing a greater food source for microbial degradation (Knoblauch et al. 2011), the present review study confirms this correlation. Biochar from manure significantly increased total microbial respiration, while biochar from wood and agricultural residues showed no significant response (Table 4). Biochar pyrolyzed at lower temperatures showed a greater ability to enhance total microbial respiration response in contrast to biochars produced by medium and high levels of pyrolysis. Consequently, some studies have proven that biochar pyrolyzed above 550 °C consistently reduces SOC and basal total microbial respiration (Saffari et al. 2020), regardless of the feedstock type. This could be due to the toxic compound production (Zimmerman et al. 2011), enhancing unstable organic carbon adsorption via high surface area and negative surface charges in high-temperature pyrolysis (Khadem and Raiesi 2017).

5 Conclusion

In this study, we quantified the impact of biochar on three key components of SCC. Our research shows that biochar has a significant positive impact on C sequestration, being a remedy for less pollution. However, its impact on total microbial respiration and total CO_2 flux showed statistical insignificance, indicating no considerable effect on these components of SCC after biochar application. We determined predictors that influence the response of SCC components. According to our findings, experimental design, geographic region, biochar application rate, feedstock type, and pyrolysis temperature appeared as crucial factors determining the results. For example, incubation experiments were a favorable environment for all SCC components, possibly due to their controlled conditions. The impact of field and greenhouse experiments varied between the SCC components. Across continents, the Middle East, Europe, and Asia showed potential for improving C sequestration, while the impact of biochar on total microbial respiration and total CO_2 flux in these regions remained indecisive. Increased biochar application rates could stimulate C sequestration and total microbial respiration responses. We also concluded from our results that biochar derived from manure and its digestate may positively impact total microbial respiration. By contrast, woody biochar contributed to more CO_2 flux, potentially increasing environmental emissions. Lower pyrolysis temperatures revealed the potential for improving both C sequestration and total microbial respiration, although the limited observations warrant further investigation. Our findings highlight the complex nature of biochar's impact on SCC and underscore the need for additional research to unravel its potential applications.

5.1 Practical implications and suggestions for future studies

The distribution of compiled observations in our database highlights variations in data representation, especially regarding feedstock types like manure and its digestate. Additional research is needed to assess the effects of these feedstocks on SCC components comprehensively. Moreover, the geographic distribution of biochar application experiments shows disparities, which underscores the need for more inclusive studies in diverse regions. Our analysis also reveals different observation patterns across experimental designs, with incubation and field settings yielding more extensive observations than greenhouses. This highlights the opportunity to advance our understanding of biochar effects under different experimental conditions. Longer-duration experiments and lower biochar application rates below 30 t ha^{-1} are underrepresented in our dataset. Conducting experiments with extended durations and lower application rates is crucial for carefully evaluating their impact on SCC. In the predictor analysis, certain results were based on a limited number of studies, which restricted their generalizability. For instance, there were few studies available on clay soil and greenhouse experiments in the total CO_2 flux dataset, while data on longer experimental durations and lower soil temperatures were scarce in the C sequestration dataset. These limitations should be considered in future review studies.

Biochar attributes such as C:N ratio, surface area, and cation exchange capacity (CEC) of biochar may have a notable impact on the soil C sequestration (Gross et al. 2021) and GHG emissions (Xu et al. 2021). This study could not investigate these factors due to data limitations. Future research efforts could include these aspects to improve the comprehensiveness of review studies.

The present study employed a rapid review, drawing exclusively from two bibliographic databases: Scopus and Web of Science. While the scope of this study is confined to these databases, they are extensive repositories that encompass a substantial portion of relevant studies. Broader inclusion of search databases could have supported more comprehensive results. Also, the study's search was confined to English-language publications; this constraint was driven by the common language proficiency of the review team, which facilitated consistent full-text screening, quality assessment, and data extraction.

5.2 Policy and management implications

The findings of this review offer policymakers invaluable insights into the potential of integrating biochar into agricultural practices as a sustainable strategy for mitigating climate change by sequestering carbon from the atmosphere. Our research indicates that biochar application can significantly enhance carbon sequestration, particularly when utilizing biochar pyrolyzed at lower temperatures and employing higher application rates over shorter experimental durations. Furthermore, across multiple continents including Europe, Asia, and the Middle East, biochar application has consistently shown promising results in enhancing soil carbon sequestration. These attributes underscore biochar's potential to address environmental pollution challenges. This review emphasizes biochar's capacity to stimulate the soil carbon cycle and enhance the overall response of soil carbon cycling components.

Previous research has highlighted variability in relationships among key components of the soil carbon cycle, such as CO_2 emissions, CO_2 flux, and carbon sequestration, attributed to diverse soil and biochar characteristics (He et al. 2017; Shakoor et al. 2021a, b). While some studies have not specifically addressed biochar's impact on all three components, our study stands out for its advanced meta-analysis methods and application of publication bias correction techniques. Our review suggests that biochar holds promise for mitigating CO2 emissions by effectively sequestering carbon from the atmosphere. Moreover, our findings offer valuable insights for agricultural policymakers and farmers, guiding decision-making processes concerning biochar application. This guidance addresses complexities such as different biochar types, soil management practices, and optimal application rates.

Abbreviations

IMA	Individual moderator analysis
GHG	Greenhouse gas
SCC	Soil carbon cycle
LASSO	Least absolute shrinkage and selection operator

Supplementary Information

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Below is the link to the electronic supplementary material.Supplementary material 1 (DOCX 766.7 kb)

Supplementary material 2 (XLSX 98.7 kb)

Author contributions

MB conducted screening, data extraction, and meta-analyses. MB and RM led the preparation of the manuscripts. All other authors contributed to the manuscript with their critical comments. The final manuscript has been read and approved by all authors.

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Materials availability

All supplementary information is provided in the Additional File.

Data availability

The datasets used during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

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