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Biochar

ORIGINAL RESEARCH

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Impact of biochar amendment on soil microbial biomass carbon enhancement under field experiments: a meta-analysis

Yogesh Kumar[1], Wei Ren[1*], Haiying Tao[2], Bo Tao[1] and Laura E. Lindsey[3]

Abstract

Biochar is well-accepted as a viable climate mitigation strategy to promote agricultural and environmental benefits such as soil carbon sequestration and crop productivity while reducing greenhouse gas emissions. However, its effects on soil microbial biomass carbon (SMBC) in field experiments have not yet been thoroughly explored. In this study, we collected 539 paired globally published observations to study the impacts of biochar on SMBC under field experiments. Our results suggested an overall positive impact of biochar (21.31%) on SMBC, varying widely with different climate conditions, soil types, biochar properties, and management practices. Biochar application exhibits significant impacts under climates with mean annual temperature (MAT) < 15 °C and mean annual precipitation (MAP) between 500 and 1000 mm. Soils of coarse and fine texture, alkaline pH (SPH), soil total organic carbon (STC) content up to 10 g/kg, soil total nitrogen (STN) content up to 1.5 g/kg, and low soil cation exchange capacity (SCEC) content of < 5 cmol/kg received higher positive effects of biochar application on SMBC. Biochar produced from crop residue, specifically from cotton and maize residue, at pyrolysis temperature (BTM) of < 400 °C, with a pH (BPH) between 8 and 9, low application rate (BAP) of < 10 t/ha, and high ash content (BASH) > 400 g/kg resulted in an increase in SMBC. Low biochar total carbon (BTC) and high total nitrogen (BTN) positively affect the SMBC. Repeated application significantly increased the SMBC by 50.11%, and fresh biochar in the soil (≤ 6 months) enhanced SMBC compared to the single application and aged biochar. Biochar applied with nitrogen fertilizer (up to 300 kg/ha) and manure/compost showed significant improvements in SMBC, but co-application with straw resulted in a slight negative impact on the SMBC. The best-fit gradient boosting machines model, which had the lowest root mean square error, demonstrated the relative importance of various factors on biochar effectiveness: biochar, soil, climate, and nitrogen applications at 46.2%, 38.1%, 8.3%, and 7.4%, respectively. Soil clay proportion, BAP, nitrogen application, and MAT were the most critical variables for biochar impacts on SMBC. The results showed that biochar efficiency varies significantly in different climatic conditions, soil environments, field management practices, biochar properties, and feedstock types. Our meta-analysis of field experiments provides the first quantitative review of biochar impacts on SMBC, demonstrating its potential for rehabilitating nutrient-deprived soils and promoting sustainable land management. To improve the efficiency of biochar amendment, we call for long-term field experiments to measure SMBC across diverse agroecosystems.

Highlights

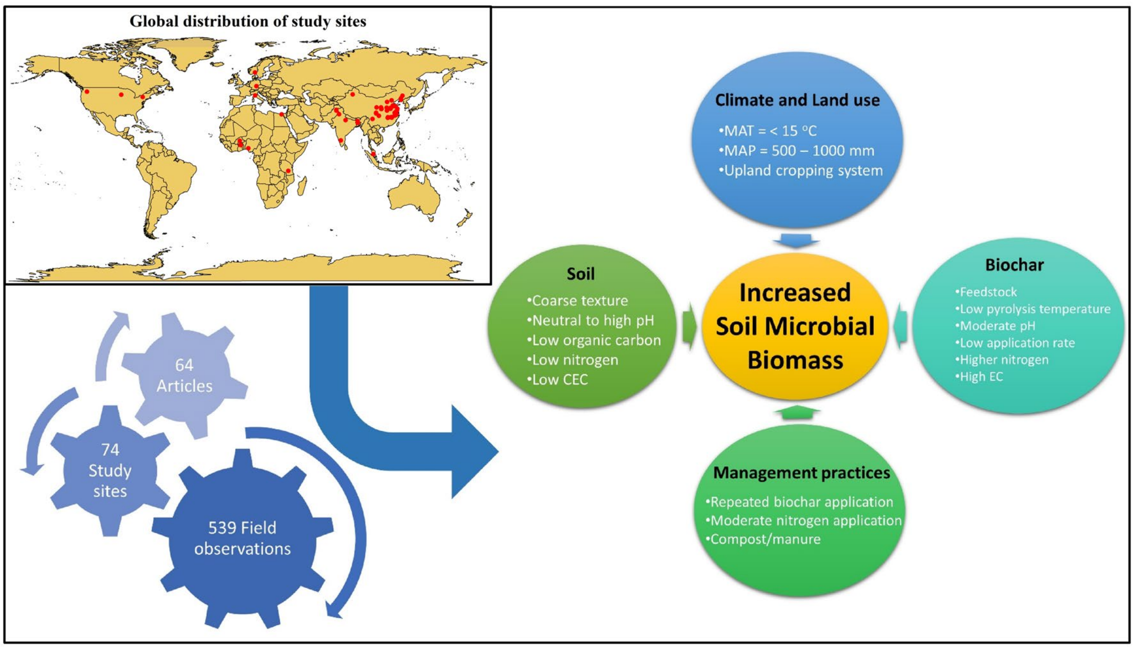
- 539 field observations were synthesized to investigate biochar impact on the microbial biomass carbon.

*Correspondence:
Wei Ren
wei.ren@uconn.edu
Full list of author information is available at the end of the article

- Biochar application increased microbial biomass carbon (SMBC), especially in degraded soil.
- Biochar impact on SMBC highly depended on the aging time of biochar in the soil.

Keywords Biochar, Char, Microbial biomass carbon, Microbial activity

Graphical Abstract



1 Introduction

Rapid global population increases, climate change, declining soil quality, and inadequate nutrient utilization have created critical challenges for food security and ecological sustainability (Darenova et al. 2022; Jones et al. 2013). While intensive agriculture can fulfill this growing food demand (Yi et al. 2022), there are numerous of studies on the adverse effects of continuing intensive agricultural practices on soil sustainability and climate (Dick 1992; Gianfreda et al. 2005; Kosmas et al. 2016; Ouyang et al. 2016; Tsiafouli et al. 2015; Withers et al. 2014). To address this challenge, Climate-Smart Agriculture (CSA) has emerged as an integrated approach to mitigate these negative environmental impacts, enhance the climate resilience of agricultural systems, and promote sustainable food production (FAO 2014, 2017).

As a widely promoted CSA practice, biochar is a carbon-rich pyrolytic solid (Mukherjee et al. 2022) stemming from plant photosynthesis, with a potential to reach negative carbon emissions (Huang et al. 2022; Yang et al. 2021) in the context of agricultural systems. Biochar can be produced from biomass materials under low or high temperatures and partial or complete absence of oxygen (Shi et al. 2021). Its application to agricultural soil represents one of the sustainable approaches for improving soil health, including soil organic carbon (SOC) sequestration (Bai et al. 2019), soil pH, aeration (Gul et al. 2015), moisture retention capacity (Igalavithana et al. 2017), nutrient availability, soil microbial biomass (Azeem et al. 2016, 2020) and nitrogen use efficiency (Majumder et al. 2019; Yang et al. 2019). Specific biochar properties, such as large surface area, high porosity, large biological affinity (Bamdad et al. 2019; Cimon et al. 2020; Xu et al. 2016), and different functional groups make it an appropriate soil amendment for enhancing nutrient retention capacity (Prommer et al. 2014). The porous structure and interstitial spaces between biochar and soil particles can retain plant-available water (Barnes et al. 2014; Liu et al. 2016a, Rasa et al. 2018), thus reducing the moisture stress during dry periods (Are et al. 2017; Ogura et al. 2016). These changes in soil properties have significantly affected the soil microbial communities, which are highly sensitive to any modification in the soil quality (Li et al. 2020a). However, previous studies have reported highly variable effects of biochar amendments on soil organic carbon content and soil microbial biomass, ranging from positive to negative, or even neutral (Liang et al. 2010; Cross and Sohi 2011; Yang et al 2022; Lu et al. 2014). These contradictory results are partly due to the complex interaction between the heterogeneous nature of the biochar, soil types, management practices, and climatic conditions (Jones et al. 2011; Zhao et al 2018). Additionally, biochar impacts on soil microbial activities greatly depends on the selection of feedstock types and pyrolysis temperature at which biochar is prepared (Rajapaksha et al. 2016; Weralupitiya et al. 2022).

Soil microbes, one of critical operators of soil biogeochemical processes, are crucial for terrestrial ecosystem stability and ecological functioning (Castrillo et al. 2017; Xu et al. 2021). These microorganisms contribute significantly to mineralization, nutrient cycling, nutrient transformation, and decomposition of recalcitrant matter (Gul et al. 2015; Yao et al. 2017; Zheng et al. 2016), playing a keyrole in maintaining soil quality and agricultural productivity (Ali et al. 2022). The SMBC and soil microbial biomass nitrogen pools are considered as appropriate indicators of soil health and function (Xie et al. 2022; Gross et al. 2014). Therefore, It is crucial to investigate the variationsin SMBC under various climates, soil types, and management practices, including the use of biochar. Research showed that biochar-amended soils have higher dissolved organic carbon and SMBC content than unamended soils (Biederman and Harpole 2013; Demisie et al. 2014; Gao et al. 2022; Lehmann and Joseph 2012; Liang et al. 2010). In contrast, Rutigliano et al. (2014) and Lu et al. (2014) did not find any significant impact of biochar application on SMBC. The application of high pH biochar to acidic soils can enhance the soil pH (Raboin et al. 2016; Rinklebe et al. 2016; Zhang et al. 2017) thus increasing the SMBC (Steiner et al. 2008). On the other hand, the application of acidic/neutral pH biochar to alkaline soils might decrease the soil pH, thereby negatively affect the soil nutrient availability (Laghari et al. 2015; Lentz and Ippolito 2012). Zhao et al. 2018 showed the positive and negative impacts of biochar prepared at different pyrolysis temperatures on the soil carbon fraction. Collectively, these studies demonstrate that the effects of biochar application vary significantly depending on heterogeneity, complex physio-biochemical properties, and the microbial activities (Joseph et al. 2021; Murtaza et al. 2023). The physical and chemical composition of biochar is significantly influenced by the feedstock types (Bamminger et al. 2016; Xiang et al. 2023) and the pyrolysis temperature during biochar production (Bruun et al. 2012; Sedlakova et al. 2021). Additionally, the impact of biochar application relies on the attributes of the targeted soil (Haefele et al. 2011; Sedlakova et al. 2021; Wu et al. 2018) and the rate at which biochar is applied (Das et al. 2021a; Dempster et al. 2012; Gomez et al. 2014). In other words, biochar effects on SMBC depends on numerous parameters, therefore, cannot be cannot be generalized.

The co-incorporation of biochar and compost positively affects soil quality (Abideen et al. 2020) and boosts the impacts of biochar on soil microbes. The high cation exchange capacity (CEC) of biochar (Mukherjee and Lal 2013) helps retain the compost/manure nutrients (Darenova et al. 2022), leading to improved crop yields. Within this framework, the combined application of biochar and other organic materials (compost or manure) can also be a promising management practice (Dey and Mavi 2022; Manirakiza et al. 2019; Rahman et al. 2022; Seki et al. 2022; Wang et al. 2022). This strategy could increase the soil microbial biomass and crop yield significantly relative to the application of nitrogen fertilizer alone (Xie et al. 2022) and reduce the nitrogen application by 20% to achieve exact crop yield. A plausible explanation could be that the labile organic matter fraction decomposes rapidly, providing additional carbon and nutrients to soil microorganisms and eventually increasing microbial activities (Zhou et al. 2020).

In addition, most of data in previous meta-analyses came from greenhouse and laboratory experiments, with little emphasis on field studies (He et al. 2017; Song et al. 2016). The potential impact of biochar on SMBC in field conditions still needs to be well explored (Siedt et al. 2021). We conducted this meta-analysis to fill this knowledge gap by focusing on field experiments in diverse climates, soils, crop management practices, and land-use types. The study aims to address the following hypotheses and objectives: (i) the impacts of biochar amendment on the SMBC in field conditions, (ii) the co-application of biochar and other organic additives (straw, compost/manure) leads to an additional effect on microbial biomass, and (iii) identify the critical indicators that affect the response of SMBC to biochar application.

2 Material and methods

2.1 Data collection

Publications that conducted field experiments to study the impact of biochar amendment on SMBC were collected using Google Scholar and Web of Science by August 2022. We used the keywords "biochar" and "microbial biomass" to filter out potential articles. Then, we screened the articles by using the following conditions: (1) the studies included at least three replications per treatment; (2) the experimental site and the environmental conditions were the same for both control and biochar treatment; (3) the study reported major biochar and soil properties. Based on these conditions, we collected 539 comparisons (with and without biochar) from 64 research articles (Fig S3) around the globe (see Annexure 1 in the supplementary information for the list of selected articles). The mean and standard deviation (SD) or standard error (SE) values were extracted from the figures using GetData Graph Digitizer 2.26 (http://getdata-graph-digitizer.com).

For those studies with only the SE provided, we used this equation $SD = SE\sqrt{n}$ to calculate the SD value. When no SD and SE values were given in the articles, we assigned one-tenth of the mean value as the SD (Liu et al. 2013). The soil organic matter values reported were multiplied with a conversion factor of 0.58 to obtain the total soil organic carbon (Mann 1986). We used the USDA soil classification system to categorize the soil textural classes based on the sand, silt, and clay proportions. When the pyrolysis temperature was provided as a range, the average values were used. The results of biochar impact on SMBC were collected, including mean, SD, and the number of replications (n) of the biochar treated and control group. In addition to the SMBC, other details such as (i) first author, (ii) climatic conditions and land use types, (iii) location (latitude, longitude, region, and country), (iv) soil properties (texture, %sand, %silt, %clay, pH, total organic C and total N content, SCEC), (v) biochar characteristics (feedstock types, pyrolysis temperature, ash content, total C and N content, application rate, application type, age, and EC), and (vi) additional management practices, such as co-application with straw, other organic materials (compost or manure), and chemical fertilizer application, were collected. A concise summary of the data collected to conduct the analysis are given in Table 1.

2.2 Meta-analysis of data

A random-effect meta-analysis model explored how SMBC interacts with various biochar types under different soil conditions and management practices. The data were analyzed in the “metafor” package of the R software version 4.3.1 (R Development Core Team 2009).

The response ratio (RR) was defined as the ratio between the results of SMBC in biochar treatment and the control group. The natural log-transformed RR (lnRR) was used to calculate the biochar-induced effect

Table 1 The data categorization scheme used in this study

Groups	Variables	Categories
Climate and land use types	Mean annual temperature (°C)	< 10, 10–15, and ≥ 15
	Mean annual precipitation (mm)	< 500, 500–1000, 1000–1500, and ≥ 1500
	Land use types	Upland (wheat, maize, cotton, barley, peanuts, oats, and beans), lowland (rice), lowland/upland (rice-maize, rapeseed-maize, rice–wheat, and mustard-rice), and forestry (trees, and bamboo)
Soil properties	Texture	coarse (loamy sand, sandy and sandy loam), medium (loamy, silt, sandy clay loam, and silt loam), and fine (clay, clay loam, silty clay, and silty clay loam)
	Soil pH	< 5, 5–6, 6–7, 7–8 and > 8
	Total organic carbon (g/kg)	< 5, 5–10, 10–15, 15–20, and > 20
	Total nitrogen (g/kg)	< 0.5, 0.5–1.0, 1.0–1.5, 1.5–2.0 and > 2.0
	Soil CEC (cmol/kg)	< 5, 5–10, 10–20, and > 20
Biochar properties	Feedstock	Crop residue (such as straw, stover, stalk, cob, and bagasse), poultry manure and wood (branches, wood pellets, nutshells, wood chips, and softwood)
	Biochar application rates (t/ha)	< 10, 10–20, 20–30, 30–40, and ≥ 40
	Biochar application type	Single, Repeated (annual and seasonal)
	Biochar aging time (months)	≤ 6, 7–12, 13–24, 25–36, and > 36
	Pyrolysis temperature (°C)	Less (< 400), medium (400–500), high (500–600), and very high (≥ 600)
	Biochar pH	< 8, 8–9, 9–10, and > 10
	Biochar carbon (g/kg)	< 300, 300–500, 500–700, and > 700
	Biochar nitrogen (g/kg)	< 5, 5–10, 10–15, and ≥ 15
	Biochar ash (g/kg)	< 100, 100–200, 200–400, and > 400
	Biochar total surface area (m^2/g)	< 10, 10–20, > 20
	Biochar EC (dS/m)	< 10, > 10
Management practices	Biochar + nitrogen application (kg/ha)	< 150, 150–300, ≥ 300
	Biochar + manure or compost	–
	Biochar + straw	–

size (yi) of all the paired observations (Hedges et al. 1999). The equation for lnRR is as follows:

$$lnRR = ln\left(\frac{\overline{X}_t}{\overline{X}_c}\right) = ln\overline{X}_t - ln\overline{X}_c \quad (1)$$

where $\overline{X}_t$ is the mean value of SMBC under biochar treatment and $\overline{X}_c$ is the mean value under control groups. We estimated the variance (v) of lnRR using the following equation:

$$\boldsymbol{v} = \left(\frac{\boldsymbol{S}_t^2}{\boldsymbol{n}_t\overline{\boldsymbol{X}}_t^2}\right) + \left(\frac{\boldsymbol{S}_c^2}{\boldsymbol{n}_c\overline{\boldsymbol{X}}_c^2}\right) \quad (2)$$

where S_t is the SD values of biochar treated and S_c is the SD of the control groups, while n_t and n_c represent the sample sizes of the treatment and control groups, respectively.

The weighting factor (w) was calculated by taking the inverse of the variance. The final weighting factor (w′) was determined for each observation, which was ultimately used to analyze the mean effect size (RR_{++}). The equations to calculate the (w), (w′) and (RR_{++}) are as follows:

$$\mathrm{w} = 1/v \quad (3)$$

$$\mathrm{w}' = w/n \quad (4)$$

$$\mathrm{RR}_{++} = \left(\frac{\sum_i \boldsymbol{lnRR}'_i}{\sum_i \boldsymbol{w}'_i}\right) \quad (5)$$

where lnRR′ = w′ lnRR is the weighted effect size, i represents the ith observation, and n indicates the total number of observations per the study. 95% confidence intervals (CI) of lnRR_{++} were calculated to determine the statistical significance of biochar application, and the results were only considered significant if CI did not overlap with zero. The effect size was then converted into percent change [$(e^{(RR++)} - 1) \times 100\%$] to better visualize the results (Huang et al. 2018).

The relative importance of predictor variables on the effect size of SMBC fractions was determined through the Generalized Boosted Regression Modeling method using the gradient boosting machines (GBM) package in the R version 4.3.1. Fifteen predictor variables were tested, including climatic conditions (MAT and MAP), biochar properties (BTM, BTC, BTN, BAGE, BAP, and BPH), soil properties (sand, silt, clay, STC, STN, and SPH), and nitrogen application which were used to calculate the relative influence (%) on biochar-induced effect size (yi). To find the best-fit model with the lowest root mean square error (RMSE), a total of 144 model combinations were analyzed with a different set of hyperparameters such as shrinkage/learning rates (0.01, 0.05, 0.001, and 0.005), interaction depth (3, 4, 5, and 7), the minimum number of observations in the terminal node (5, 10, and 15) and bag fraction (0.5, 0.6, and 0.7) using 10-fold cross-validation and 6000 trees. Among the fitted models, the best-fit model with RMSE of 0.2235 had the parameter values: learning rate (0.05), bag fraction (0.50), interaction depth (7), and the minimum number of observations in the terminal node (10). The Gaussian distribution of squared error was used to fit the models because the variables were in continuous intervals. The Pearson correlation coefficient was utilized to explain further the inter-relationship between the complex climate conditions, fertilizer application, biochar, and prior soil properties.

Publication bias was assessed using a funnel plot (Fig. S1) that depicted the log ratio of mean effect size and its standard error (Egger et al. 1997). If the mean effect had a significant difference from zero (i.e., indicating the existence of publication bias), we further used Rosenthal's method provided in the file drawer analysis package in R version 4.3.1 to estimate whether our conclusion was affected by the nonpublished data (Rosenberg 2005; Rosenthal 1979). A large Rosenthal's Fail-Safe number (1138867) was obtained, exceeding the threshold of $5n + 10 = 2705$ (where n is the number of observations in the analysis). This confirmed the absence of bias in our study and suggested that our conclusion may be independent of publication bias (Fragkos et al. 2014).

3 Results

3.1 Biochar alone vs. combined with other management practices

The meta-analysis included 539 observations from diverse global studies investigating the impacts of biochar on the SMBC under field experiments. Our results showed that there was an overall significant increase of 21.31% (539) in the SMBC with biochar applied alone or combined with other inputs as a soil amendment (Fig. 1). However, when biochar was the only soil amendment, the increase in SMBC was 10.18% (87), which is significantly less as compared to the overall effects. The co-application of biochar and nitrogen fertilizer displayed a remarkable effect size of 23.75%, with 415 observations suggesting a widespread management practice. The different amounts of the nitrogen application, such as < 150, 150–300, and ≥ 300 kg/ha, had varied effect sizes of 15.49%, 27.92%, and 28.56%, respectively. The results indicated that a nitrogen application rate of 150–300 kg/ha significantly increased the SMBC; there was no further improvement in SMBC with more nitrogen fertilizer

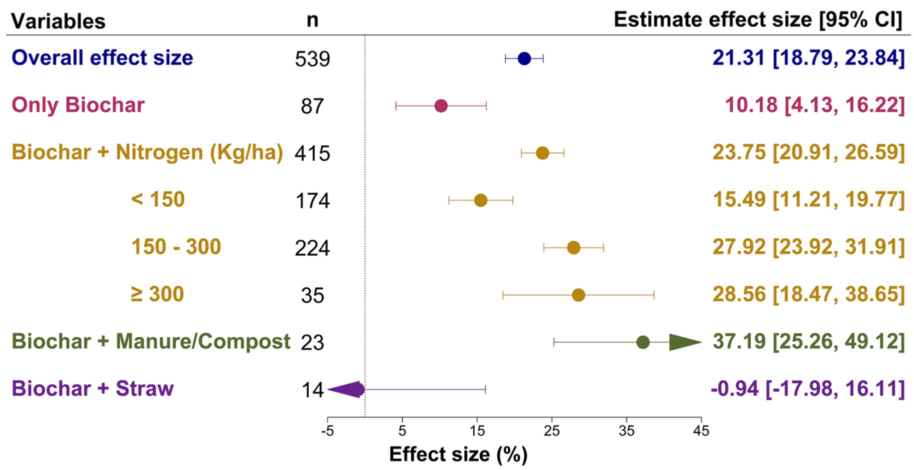


Fig. 1 Percent change in the biochar effect on soil microbial biomass carbon under different management practices. (n is the number of paired observations)

application. In contrast, the co-application of biochar and straw had no significant effect on SMBC.

Additionally, biochar application in combination with other organic amendments such as compost or manure resulted in a higher effect size of 37.19% (23) among all the management practices. These results illustrate the varying impacts of biochar under various management techniques and the potential impact of additional inputs such as nitrogen fertilizer application, straw, and manure/compost on the SMBC.

Relative influence of predictor variables on the biochar-induced effect size: The results from the GBM showed the relative influence of different predictor variables on the biochar-induced effect size (Fig. 2). The observations suggested that the biochar properties (46.2%) had the highest relative influence, followed by soil properties (38.1%), climatic conditions (8.3%) and nitrogen application (7.4%). The soil clay fraction was the most important among the soil properties, following SPH, STC, STN, sand, and silt fraction. BAP had a significant impact within the biochar properties, followed by BAGE, BTN, BPH, and BTM. The climatic conditions, i.e., MAT and MAP, had a moderate effect at 5.5% and 2.8%, respectively. Nitrogen application had a 7.4% influence on the biochar impacts on SMBC.

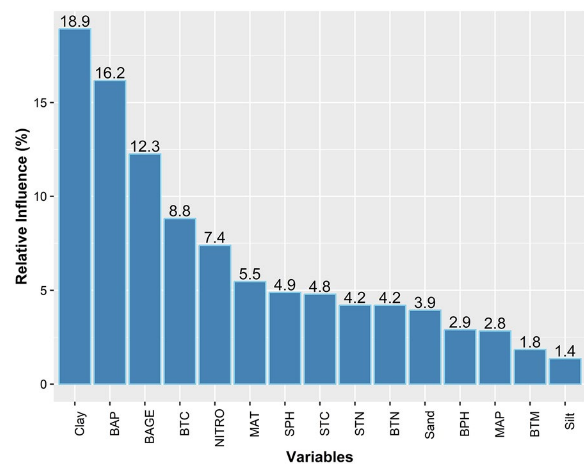


Fig. 2 Relative influence of different predictor variables on the biochar-induced effect size. *Clay* clay fraction, *BAP* Biochar application rate, *BAGE* Biochar aging time, *BTC* Biochar Total Carbon, *NITRO* Nitrogen application, *MAT* Mean Annual Temperature, *SPH* Soil pH, *STC* Soil Total Organic Carbon, *STN* Soil Total Nitrogen, *BTN* Biochar Total Nitrogen, *Sand* Sand fraction, *BPH* Biochar pH, *MAP* Mean Annual Precipitation, *BTM* Biochar pyrolysis Temperature, and *Silt* Silt fraction

Correlation between the climate conditions, fertilizer application, biochar, prior soil properties, and the biochar-induced effect size: A correlation matrix was used to assess the relationship between biochar application in different climatic and prior soil conditions (Fig. 3). The results showed that nitrogen application had a positive relationship with sand fraction (%), SPH and biochar-induced effect size, but had a negative relationship with clay fraction (%), STC and STN (Fig. 3). MAT and MAP were negatively correlated with biochar-induced effect size. Among the biochar properties, BTM and BTC had a negative relationship with biochar-induced effect size, but BPH and BTN had no significant relationship. In the soil properties, silt fraction, clay fraction, STC, and STN were negatively correlated with biochar-induced effect size. On the other hand, sand fraction and SPH were positively correlated with biochar-induced effect size. The clay fraction that had the most significant influence on the biochar-induced effect size showed a positive relationship with STC, MAP, and BTM and a negative with MAT, BTC, BTN, SPH, STN, and nitrogen application.

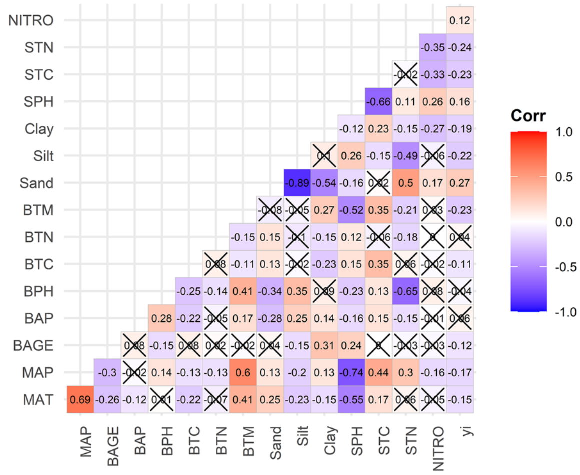


Fig. 3 The correlation between the climatic conditions, biochar, prior soil properties, and biochar-induced effect size. *MAP* Mean Annual Precipitation, *BAGE* Biochar aging time, *BAP* Biochar application rate, *BPH* Biochar pH, *BTC* Biochar Total Carbon, *BTN* Biochar Total Nitrogen, *BTM* Biochar pyrolysis Temperature, Sand fraction, Silt fraction, Clay fraction, *SPH* Soil pH, *STC* Soil Total Organic Carbon, *STN* Soil Total Nitrogen, *NITRO* Nitrogen fertilizer application, yi = biochar induced effect size. The cross represents the non-significant relationship (p-value > 0.05)

The second influential variable, BTC, was negatively correlated with MAP, MAT, BTM, clay fraction, and BPH and positively correlated with sand fraction and SPH. The results also showed that STC, STN, MAP, MAT, and BTM strongly correlated negatively with SPH.

3.2 Biochar application under various climatic conditions and land-use types

Mean annual temperature: The results suggested that biochar significantly improved the SMBC under all MAT conditions, but effects were more pronounced at temperatures < 15 °C (Fig. 4). The highest increase 34.21% (164) was observed at temperature range between 10 and 15 °C, followed by 28.81% (102) at temperature of < 10 °C, while the lowest effect 7.98% (202) was observed at temperatures ≥ 15 °C. *Mean annual precipitation:* The effect size differed with different precipitation levels (Fig. 4). Biochar amendment had the greater significant positive effect of 32.45% (239) in regions with a precipitation range of 500–1000 mm. In areas with precipitation < 500 mm and > 1500 mm, the effect sizes were 18.95% (39) and 19.11% (68), respectively. When the MAP was in the range of 1000-1500 mm, no significant effect of 5.02% (130) of biochar was observed.

Land-use type: The analysis indicated significant associations between land-use types and SMBC (Fig. 4). Upland had a significantly higher increase of 29.76% (364), followed by lowland with an effect size of 12.57% (71). While the effect size of Forestry and the mixture of lowland and upland land use types was 3.20 (62) and 1.28 (42), respectively, they had no significant improvements in the SMBC with biochar application. Given that various land use types can considerably impact SMBC, our findings emphasize the need to consider land use when researching microbial dynamics and ecosystem functioning.

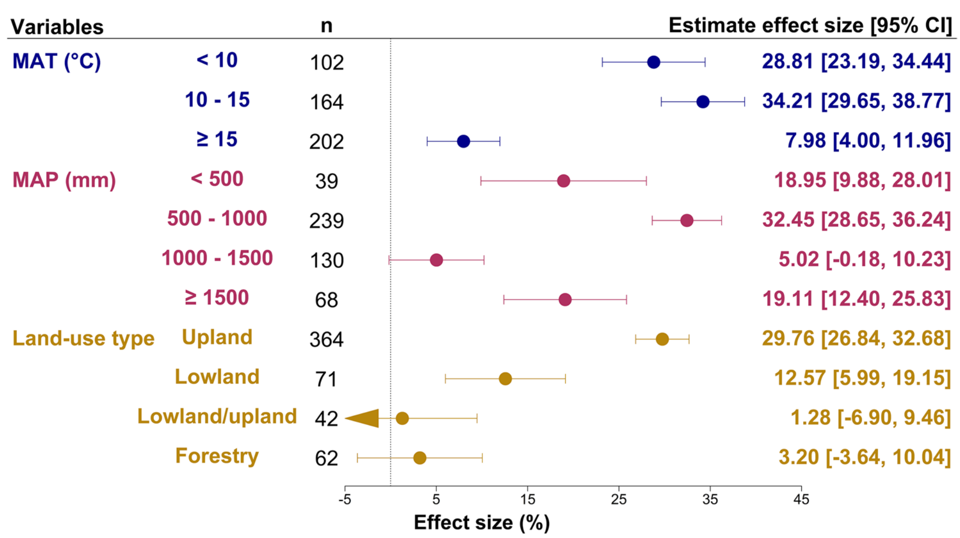


Fig. 4 Percent change in the biochar effect on soil microbial biomass carbon under varied climatic and land-use types. (n is the number of paired observations)

3.3 Biochar application under different soil properties

Soil texture: The results indicated that biochar application significantly affected SMBC across all soil textural classes (Fig. 5). However, a higher increase was seen in the coarse 26.47% (188), followed by fine-textured soils with 21.90% (100), compared to the effect size of 16.84% (231) in medium texture soil. *Soil pH:* The effect of biochar amendment on SMBC varied across different SPH levels (Fig. 5). The results indicated that biochar application positively affects SMBC across all SPH levels.

The highest effect size of 29.99% (148) was observed in SPH ≥ 8, followed by SPH between 7–8, 6–7, and < 5 was 26.44% (98), 22.37% (68) and 18.26% (64), respectively. The lowest effect size of 12.23 (116) was found when the SPH was 5–6. *Soil Total Organic Carbon:* The results indicated that the effect size varied depending on the initial level of STC (Fig. 5).

The largest effect size was 32.70 (99) for soils with 10–15 g/kg, followed by 31.01 (199) for soils with 5–10 g/kg and 18.89% (40) for soils with < 5 g/kg STC. Concurrently, when the STC was higher than 15 g/kg, there was no significant improvement in the biochar impact on SMBC. *Soil Total Nitrogen:* The results indicated that prior STN content significantly affected the biochar impact on SMBC (Fig. 5). The results showed a decrease in effect size with an increase in the STN except for the STN range between 1.0 and 1.5 g/kg. The greater impact of 47.24% (39) in effect size was found at STN level 1.0–1.5 g/kg, followed by 37.12 (30) at < 5 g/kg, 20.77% (139) at 0.5–1.0 g/kg and 5.37% (115) at 1.5–2.0 g/kg. No significant increase in effect size was found in soils with higher levels of total nitrogen (≥ 2.0 g/kg).

Soil CEC: The results revealed that the effect of biochar application on SMBC varied significantly with the initial SCEC (Fig. 5). Biochar application to low SCEC soils (< 5 cmol/kg) had the highest positive impact of 41.89% (24), followed by high SCEC soils (> 20 cmol/kg) with an effect size of 29.60 (18). When biochar was applied to soils with intermediate SCEC (5–10 cmol/kg) , this resulted in lower effects of 8.92 (48), and a non-significant effect was found when the SCEC was in the range of 10–20 cmol/kg. These results proposed that biochar

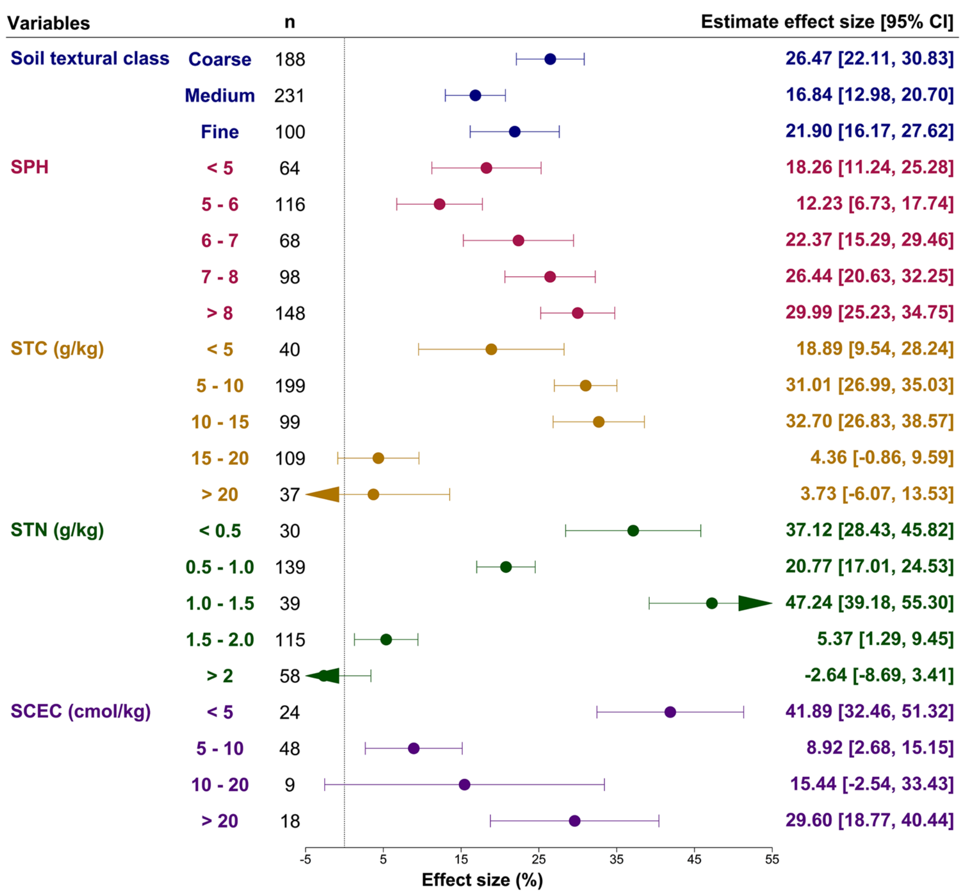


Fig. 5 Percent change in the biochar effect on soil microbial biomass carbon under different soil conditions. (*n* is the number of paired observations)

application may be most beneficial for improving SMBC in less fertile soils with sandy texture and low STC, STN, and SCEC levels.

3.4 Effects of biochar properties

Biochar pyrolysis temperature: Our meta-analysis showed that low BTM showed better impact on SMBC (Fig. 6). The highest significant increase of 42.63% (73) was found at < 400 °C, followed by 23.89% (209) at 400–500 °C, 13.85% (157) at 500–600 °C, and 9.38% (73) at ≥ 600 °C. *Biochar application rate:* The results revealed that biochar at all application rates increased SMBC notably (Fig. 6). Biochar applied at < 10 t/ha showed a higher increase of 26.95% (229) compared to the other application rates. The application rate showed a decreasing trend with the higher application rates. *Biochar pH:* The study found that different BPH levels showed no correlation with biochar-induced effect size (Fig. 6). The largest effect size of 46.01% (106) was observed in the range of 8–9, followed by 24.58% (148) at > 10 and 12.74% (223) at 9–10 BPH. There was no significant improvement in the effect size when BPH was < 8. *Biochar Total carbon content:* The higher increase of 48.08% (12) was found when the BTC was < 300 g/kg, followed by 23.69% (106)

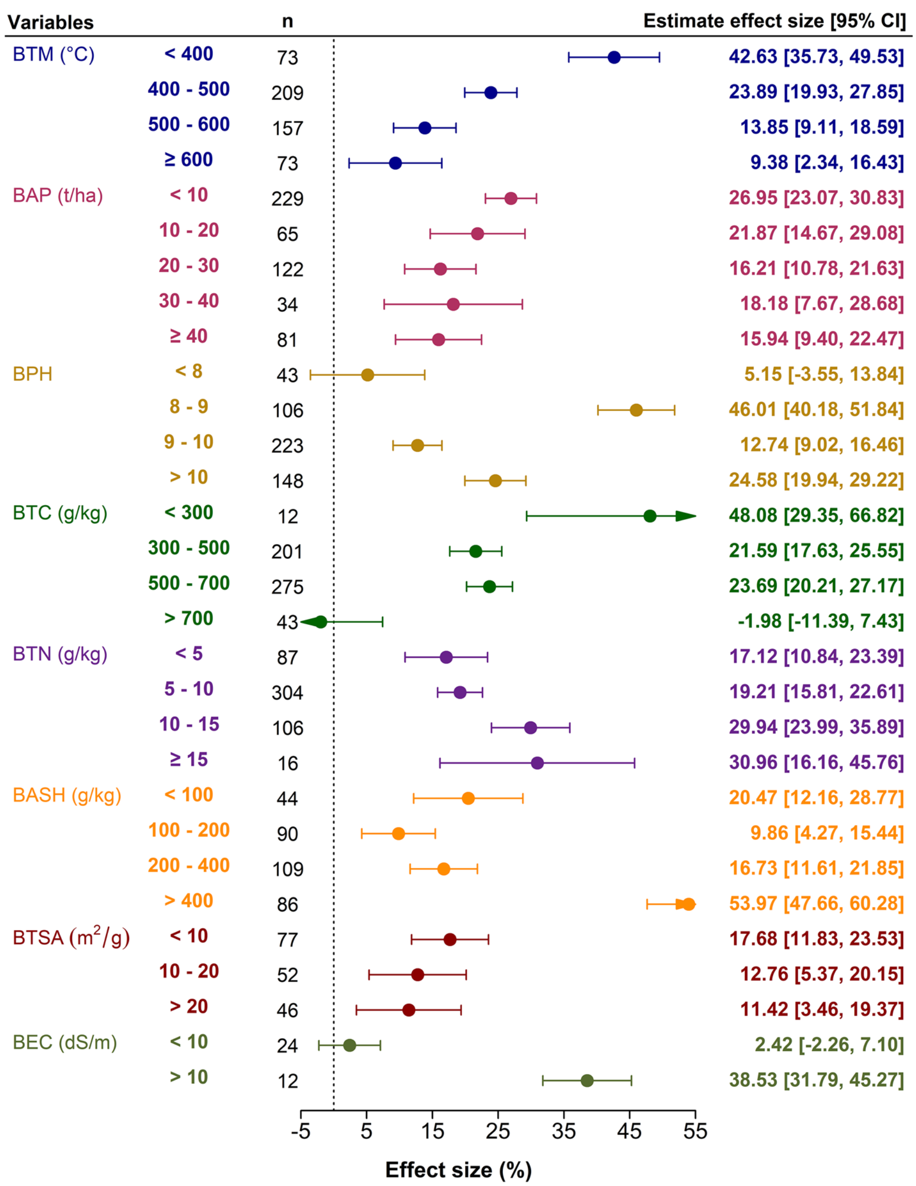


Fig. 6 Biochar effect on soil microbial biomass carbon under different biochar characteristics. (*n* is the number of paired observations)

at 500–700 g/kg and 21.59% (304) at 300–500 g/kg of BTC (Fig. 6). A negative effect size of -1.98% (43) at BTC higher than 700 g/kg. These findings suggested that biochar with low to moderate total carbon content may be more effective in promoting microbial biomass carbon. *Biochar total nitrogen content:* Biochar was found to be more effective at higher BTN (Fig. 6). The highest effect size of 30.96% (16) was found when the BTN was ≥ 15 g/kg, followed by 29.94% (106) at 10–15 g/kg, 19.21% (304) at 5–10 g/kg, and lowest effect size 17.12% (87) was found when the BTN was less than 5 g/kg.

Biochar ash content: The largest effect size of 53.97 (86) was observed with ash content of > 400 g/kg, followed by 20.47% (44) at < 100 g/kg, 16.73% (109) at 200–400 g/kg, and lowest increase of 9.86% (90) was found at 100–200 g/kg (Fig. 6). *Biochar total surface area:* The results showed no significant difference between varied biochar surface areas (Fig. 6). Still, the highest increase of 17.68% (77) in SMBC was observed in lower biochar surface area (< 10 m^2/g). The improvement in the SMBC sat biochar surface area of 10–20 and > 20 m^2/g was 12.76% (52) and 11.42% (46), respectively. *Biochar Electrical conductivity:* The biochar with higher EC was found to be more effective (Fig. 6). The biochar with EC less than 10 dS/m resulted in an effect size of 2.42% (24), while biochar with EC greater than 10 dS/m showed a significantly higher effect size of 38.53% (12). *Feedstock type:* The results indicated no significant difference among the varied feedstock types; crop residue showed an effect size of 22.63% (457), wood had 13.45% (78), and poultry manure had 37.77% with only two observations (Fig. 7). Within the different crop residues, cotton and maize showed superior effect on the SMBC with the effect size of 55.55% (13) and 39.57% (137), respectively. The other crop residue types, such as rice, and wheat, were statistically comparable, but sugarcane showed no improvements on SBMC. *Biochar application type and age:* The results showed that biochar application type and its aging time in the soil significantly impacted the positive effects of biochar (Fig. 8). Single-time biochar application resulted in a 13.62% increase in the SMBC, while the repeated biochar application led to a much higher increase of 50.11%. Furthermore, the aging time of biochar in the soil also played a crucial role in its positive impacts on SMBC. Biochar aging time for ≤ 6 months resulted in an increase of 18.71%. As the aging time of biochar in the soil increased, the positive impacts on SMBC decreased, with biochar aging time between 25 and 36 months showing an increase of 20.67%. Biochar aging time for more than 36 months exhibited the lowest non-significant increase of 6.42%.

4 Discussion

4.1 SMBC in biochar-amended soils under different management practices

The findings of this meta-analysis contribute to our comprehension of biochar's effects and additional inputs on SMBC in different climatic, land-use, soil, and biochar properties. The overall positive effect observed in SMBC proposed that biochar significantly enhances soil microbial activity. These findings are consistent with previous meta-analysis studies that have illustrated the beneficial impact of biochar on soil microbial communities (Chagas et al. 2022; Pokharel et al. 2021a, b; Liu et al. 2016b; Li et al. 2020b). Our analysis has shown that combination of biochar and nitrogen fertilizer demonstrated a synergistic effect on SMBC. Biochar combined nitrogen fertilizer resulted in improved soil bulk density (Li et al. 2020a), additional nutrient supply, promoted soil organic carbon

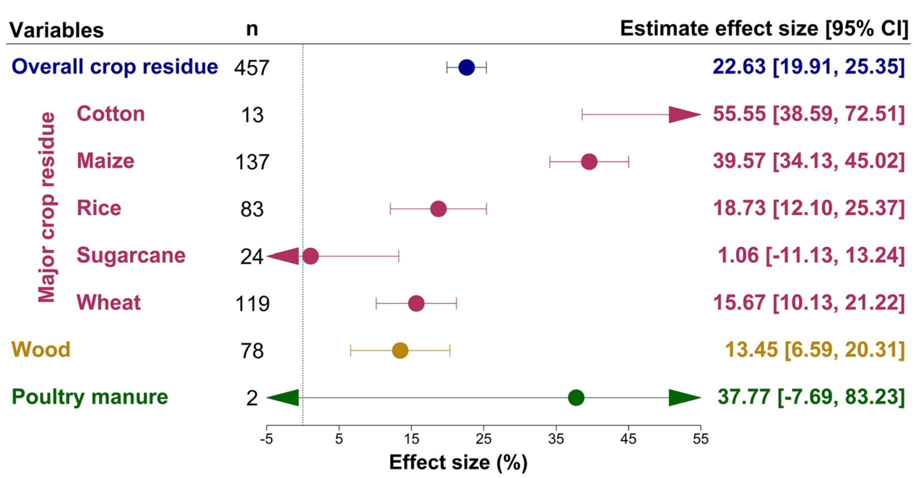


Fig. 7 Biochar effect on soil microbial biomass carbon under different biochar feedstock types. (*n* is the number of paired observations)

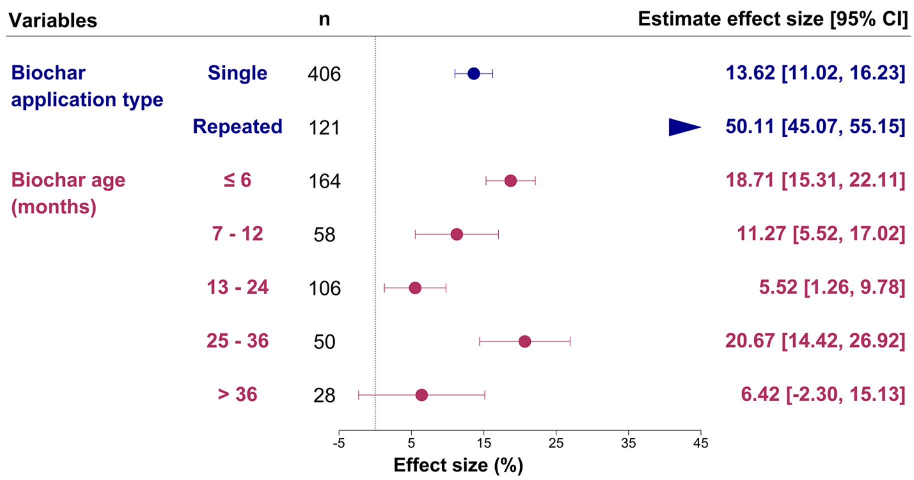


Fig. 8 Biochar effect on soil microbial biomass carbon under different biochar application types and age. (*n* is the number of paired observations)

and total nitrogen accumulation in the soil (Saha et al. 2019; Wu et al. 2019a,b), especially in low fertile soils (Dong et al. 2021), resulting in the enhancement in the soil quality and SMBC (Lopes et al. 2021; Xia et al. 2022). Fritz et al (2022) concluded that biochar combined with nitrogen fertilizer improved microbial habitat conditions due to increased respiratory response and reduced carbon limitation. Another possible explanation for increased SMBC with the co-application of biochar and nitrogen application is the reduced negative effects of nitrification-induced pH decline (Häring et al. 2017). Oladele et al. (2019) observed that the co-application of biochar and nitrogen fertilizer created a nutrient-rich soil environment ideal for microbial growth and hence increased SMBC content. Other studies conducted by Dong et al. (2022) and Sun et al. (2022) have also reported that biochar amendment increases SMBC, especially when applied with nitrogen fertilizer rather than when used alone. These findings are supported by research highlighting the capability of biochar to enhance nutrient retention and cycling in soil ecosystems (Hossain et al. 2020). Additionally, the results regarding nitrogen application rates revealed that exceeding a certain threshold may not enhance microbial biomass further (Ali et al. 2022). This result aligns with previous studies suggesting that excessive nitrogen inputs do not yield a proportional increase in microbial biomass and may negatively affect overall soil quality (Asirifi et al. 2021; Jun et al. 2007; Ullah et al. 2023). These findings emphasize the importance of optimizing nitrogen application rates with biochar to maximize the benefits for microbial biomass and minimize potential environmental impacts. This information could be helpful for farmers and land managers seeking cost-effective ways to improve soil health and productivity using organic amendments.

Furthermore, our study showed that combining biochar with organic amendments, such as compost or manure, substantially affects SMBC. This suggests that biochar and compost or manure applied together lead to synergistic effects, which could be ascribed to improved soil structure, enhanced organic carbon content, and increased nutrient availability that can provide favorable conditions for microbial growth (Bera et al. 2016; Singh et al. 2018). This is because the decomposition of organic constituents of compost/manure releases nutrients into the soil. The organic amendments amplify the positive impacts of biochar on SPH by enhancing phosphorus availability (Du et al. 2020; Glaser and Lehr 2019; Lima et al. 2021). Apori et al. (2021) concluded that the combination of biochar and manure increased the SPH and STC due to the organic carbon contributed by the biochar and the supplementary carbon from the organic matter introduced by the manure (Grunwald et al. 2016). While Lima et al. (2021) argued that the positive impacts of the combined application of biochar and other organic amendments greatly depend on the soil texture. In contrast, when the biochar was applied with nitrogen fertilizer, the soil microbes rely solely on the carbon substrate from the biochar (Oladele et al. 2019). Similarly, Frimpong et al. (2016) also reported that increased STC following the co-application of biochar and manure simulated carbon sequestration and accumulation. The biochar and manure applied together could potentially improve the nutrient use efficiency of the manure, reduce nutrient leaching, reduce bulk density, and improve soil structure and nutrient retention ability (Agbede et al. 2022). Dey and Mavi (2022) demonstrated that when biochar is applied with other organic inputs (animal manure and rice residue), it leads to higher carbon mineralization, increased release of readily available nutrients, and tremendous microbial growth compared to soil amended solely with biochar. Overall, biochar and manure application improve soil health and make it nutrient-rich, thus increasing the SMBC. This finding underscores the significance of considering multiple organic inputs to enhance soil microbial activities and biomass. However, it is essential to note that not all management practices or combinations resulted in positive effects. When biochar was applied with straw, it had a small negative effect size of -0.93 percent, suggesting a potential interference between biochar and straw in this context. A possible explanation is that the higher C:N ratio of straw as an organic amendment leads to nitrogen immobilization (Said-Pullicino et al. 2014). Soon (1998) found that incorporating straw residue resulted in lower SMBC. A long-term field study in Oregon showed a 32% decrease in the soil organic carbon content due to continuous straw incorporation (Collins et al. 1992). Additionally, the incorporation of low-nutrient straw residue may have detrimental impacts on microbial activity (Black and Reitz 1972). The decomposition of straw requires significant microbial activity, causing high carbon demand by microbes, thus leading to subsequent reduction in SMBC. Our results demonstrate the complexity of interactions between biochar and different organic materials, which can be influenced by any biotic or abiotic factors affecting the impact of biochar. Similarly, other studies in Alberta, Canada, by Malhi et al. (2012) found no difference in SMBC under the straw application. It is essential to take into account the particular climatic and soil conditions when determining the suitable supplementary inputs with biochar application (Wang et al. 2021).

4.2 SMBC in biochar-amended soils under different climates and land-use types

It is widely recognized that abiotic factors such as precipitation and temperature play a significant role in shaping soil microbial activity (Campbell & Biederbeck 1976; Curtin et al. 2012; Li et al. 2002; Mehta et al. 2014; Qu et al. 2023). In this study, biochar significantly increases the SMBC under all the MAT and MAP conditions. However, the highest percentage increase was seen in low MAT and MAP areas because, under these environmental conditions, there is limited microbial activity, nutrient cycling, and soil moisture (Lipson et al. 2000; Schimel and Schaeffer 2012). Therefore, the higher effect size of biochar application observed under MAT < 15 °C and MAP < 1000 mm may be attributed to biochar's ability to alleviate the adverse impact of low temperatures on soil microbial activity and increase soil water holding capacity (Li et al. 2018). Biochar has the potential to serve as a physical barrier to protecting microbial communities from cold stress (Cayuela et al. 2013) and creating a conducive environment for soil microbes to sustain in low-temperature environments (Gul et al. 2015; Radziemska et al. 2022). On the other hand, in areas with high MAT, MAP, and forest soils, the percentage increase in SMBC was relatively lower. This observation can be explained by the fact that high MAT, MAP, and forest land naturally lead to increased microbial activity, resulting in a higher baseline level of SMBC (Baligh et al. 2021; Hassan et al. 2022; Mehta et al. 2014). Consequently, the incremental impact of biochar application on SMBC is less pronounced in these warmer, high-precipitation and forest land-use regions. The results also revealed that biochar's impact on SMBC greatly depends on the land-use type of treated soil. Other studies also reported that soil physio-biochemical properties substantially alter with diverse land-use types (Kara and Bolat 2008; Lepcha and Devi 2020), and biochar exhibits varied effects among different land-use types (Pokharel et al. 2021a, b).

4.3 SMBC in biochar-amended soils under different edaphic conditions

The existing literature has explored how biochar application possibly alters soil characteristics (Abujabhah et al. 2016; Lehmann et al. 2003; Zhang et al. 2021b). In this analysis, we have summarized the biochar-induced changes in SMBC when applied to different soil physical and chemical characteristics. Das et al. (2021b) argued that soil microorganisms are sensitive to changes in the soil environment. The favorable habitat differs among the different microbial groups, and adding biochar to a particular soil environment tends to stimulate only certain types of microorganisms, not all of the microbial biomass present in the soil (Khadem and Raiesi 2017; Steinbeiss et al. 2009). Biochar amendment to coarse and fine-textured soil leads to increased SMBC, with a more prominent increase observed in coarse-textured soil, partly due to the large surface area and porosity of biochar. Therefore, soil can hold more air and water (Lehmann et al. 2011; Palansooriya et al. 2019; Tomczyk et al. 2020), fostering higher organic matter and creating promising conditions for the proliferation and functioning of microorganisms (Chagas et al. 2022). A recent experiment by Singh et al. (2022) also reported that incorporating biochar into coarse-textured soils improves the SPH, porosity, and SCEC. Coarse-texture soils, known for their low clay fraction, organic matter, SCEC, and fertility, benefit significantly from biochar amendment as a source of organic matter. This additional input in coarse-texture soils improves the concentration of organic matter, thus strongly enhancing the soil properties (Mujiyati and Supriyadi 1970). We also observed that soil clay fraction had a positive relationship with STC and a negative relationship with biochar-induced effect size, which may be because the clayey soils can preserve more soil organic matter as compared to the sandy soils (Hamarashid et al. 2010); thus biochar impact was less in these soils. In contrast, Dempster et al. 2012 and Liu et al. 2011 reported a significant decrease in SMBC in coarse texture and rice soils with Eucalyptus biochar and bamboo biochar, respectively, suggesting varied impacts of biochar feedstocks. The change in SMBC varied around various pH ranges, and the alteration in SPH with biochar input is generally because of the alkaline properties of biochar (Azeem et al. 2019; Geng et al. 2022). However, the potential of biochar to raise SPH depends on factors like absorbent nature, ash content, and basic oxide cations of the biochar (Luo et al. 2011; Novak et al. 2009). Most studies demonstrated the rising of SPH (Castaldi et al. 2011; Cheng et al. 2008; Cooper et al. 2020; Domene et al. 2014; Lehmann et al. 2003; Liang et al. 2006; Jeffery et al. 2011; Tryon 1948) in acidic soils and that could be the reason for the increase in SMBC. It is possible that biochar application can act as an alkaline buffer when applied to acidic soils can promote microbial activity and population (Biederman & Harpole 2013; Steiner et al. 2008). Additionally, the application of biochar in acidic soils increases its sorption capacity to retain more nutrients and water (Sohi et al. 2010) and provides supplementary carbon input, thus enhancing microbial growth (Meena and Prakasha 2022). Our analysis also revealed that initial SPH was the second most influential factor among the soil properties explaining the biochar-induced impact on SMBC. While it should be noted that the benefits of biochar application greatly vary with different SPH ranges such as, (Zhang et al. 2014) conducted an experiment with a BPH of 8.2, and the field SPH was 8.1, did not notice any significant improvement in the SPH but found 6–296% increase in the SMBC depending on the BAP, time of the year and soil depth, on the other hand, when (Zhang et al. 2021a) conducted an experiment with BPH of 9.48 and field SPH was 4.96, noticed significant improvement in the SPH and annual average of 13.69% increase in the SMBC. In contrast, another meta-analysis of mixed field and lab experiments showed a negative impact of biochar on SMBC with the increase in the SPH (Liu et al. 2016b). These contradictory results highlighted the importance of current research. Biochar improves the STC content due to its long turnover time and its stable carbon content (El-Naggar et al. 2019; Sun et al. 2021). STC is the carbon and energy source for the microorganisms (Sun et al. 2021), and SMBC is considered as the most sensitive part of the soil carbon dynamics (Liu et al. 2008; Sui et al. 2013), thus any changes in STC significantly stimulate the SMBC. While the initial level of the STC was the third most influential factor among the soil properties and had a negative relationship with biochar efficacy (Liu et al. 2016b). The results are consistent with research by Lehmann and Joseph (2012) that the microbial activity and increased soil carbon storage are simulated by biochar incorporation into low-carbon soils. Meanwhile, Woolf et al. (2010) also found that the effect of biochar on soil carbon storage is limited in high-carbon soils. Another meta-analysis (Chagas et al. 2022) showed that biochar can potentially boost SMBC with low to moderate STC, increasing soil fertility and productivity. However, caution should be exercised when applying biochar to high-carbon soils, as the potential benefits may be limited. Previous research conducted by Kannan et al. (2021) and Prendergast-Miller et al. (2014) reported that biochar addition reduces nitrogen leaching, and improves the mineralization of soil organic nitrogen, thus promoting soil microorganism activities. In contrast, we found a negative correlation between STN and biochar-induced effect size; it indicated that SMBC varies with initial STN. Yet, it is crucial to highlight that biochar impact on soil edaphic factors may depend on the source of the biochar, its production process, and the soil to which it is applied. The biochar's large surface area and presence of resistant aromatic groups, along with the addition of humic-like compounds, could contribute to the observed rise in SCEC after biochar incorporation (Karimi et al. 2020; Liu et al. 2012, 2021; Mahmoud et al. 1990, 2020). This significant enhancement in the SCEC has positive impacts on microbial biomass (Halmi and Simarani 2021). Although biochar effects on varied SCEC may depend on the SPH (van Zwieten et al. 2010), the major contribution of SCEC is that it represents the nutrient-holding capacity of the soil (Liang et al. 2006). Our results align with other investigations (Muhammad et al. 2014; Patel and Patra 2014; Taghizadeh-Toosi et al. 2012) and suggest that biochar application can significantly shift the SMBC in soils. The observed results can be ascribed to the enhanced nutrient availability and improved soil structure, which enhances the microbial activity and nutrient cycling.

4.4 SMBC in biochar-amended soils under different biochar properties

Biochar produced from various feedstock types exhibited varied impacts on climates and soil types (Gaskin et al. 2010; Irfan et al. 2019; van Zwieten et al. 2010). The key factors that determine the positive effect and influence the biochar chemical characteristics (such as biochar total carbon, nitrogen, EC, surface area, and pH) are feedstock type and pyrolysis temperature. This meta-analysis showed no significant difference among the feedstock types such as crop residue, wood, and manure/compost. However, amid crop residue feedstocks, cotton and maize-derived biochar applications resulted in the highest significant increase in SMBC content among the different crop residues, followed by rice and wheat. This may be because different feedstocks have varied chemical composition when produced at the same pyrolysis condition. Maize residue biochar had almost 50% more nitrogen content than the rice residue biochar prepared with the same pyrolysis process (Fritz et al. 2022). Pyrolysis temperature has a considerable contribution to the response of SMBC to biochar amendment. The results in this meta-analysis align with (Al-Wabel et al. 2019; Khadem and Raiesi 2017) that the biochar prepared at low pyrolysis temperature was shown to be positively correlated with biochar capacity to increase SMBC. Generally, biochar produced at higher temperatures displays more tolerance to decomposition, making it hard for the microbes to use it. The less effect at high pyrolysis temperature may result from a reduced volatile matter within biochar, along with increased aromaticity and recalcitrance (Ahmad et al. 2012; Cantrell et al. 2012; Zhao et al. 2013). Al-Wabel et al. (2019) and Usman et al. (2015) showed that higher BTM reduces the surface functional hydroxyl groups, nitrogen, hydrogen, sulfur, and oxygen levels in biochar samples and their bond with carbon atoms. The observed positive interactive results of BTM and BPH in our study align with the findings of prior research. The pyrolysis temperature and feedstock types play a major role in defining the change in biochar properties such as pH, pore volume, higher C: N ratio, surface area, stable-C and labile-C content that ultimately affects its usage to improve the SMBC (Angin 2013; Crombie et al. 2015; Downie et al. 2009; Ronsse et al. 2013). The CEC is directly related to BPH and increases with the increase in BPH and vice-versa (Lehmann 2007). High BTM of 450–550 °C influenced the biochar CEC, whereas biochar produced at BTM ≥ 550 °C showed high carbon stability, pH, CEC, and lower nutrient availability (Crombie et al. 2013; Masek et al. 2013). BTM above 500 °C causes structural changes such as pore widening, blockage, and increase in ash content, thus decreasing pore volume and surface area (Fu et al. 2011), hence decreasing habitable conditions for microorganisms (Jaafer et al. 2014). While it was clearly identified that an increase in pyrolysis temperature resulted in higher BPH (Gul et al. 2015) and enhanced carbon stability. However, biochar with a high pH may not be preferable for soil amendment because excessively high pH levels may lead to micronutrient deficiencies (Chan and Xu 2009). Therefore, depending on the purpose of use, different types of biochar feedstock and pyrolysis conditions should be considered in promoting soil health and productivity (Palansooriya et al. 2019). The analysis revealed that the SMBC increased in all the biochar application rates, but the lower rates of biochar had a prominent impact on SMBC. In contrast, Bhullar et al. (2019) noticed that microbial concentration in the soil is directly proportional to the biochar application rates. Additionally, higher rates of biochar can have an adverse effect on SMBC, which is evident that biochar's hydrophobic nature decreases the soil water content, and a high C: N ratio induces an immobilization of soil microbial nitrogen (Li et al. 2018); thus, leading to less microbial activities (Ameloot et al. 2013). Rather than BTM and feedstock types, our results showed that BTC was the most influential variable among the biochar properties and had a negative relationship with the biochar impacts on SMBC. Similar adverse impacts of high BTC were also noted by Liu et al. (2016b), and this can be explained by the fact that high BTC often results in the immobilization of the soil inorganic nitrogen (Cayuela et al. 2013), reducing the availability of the soil nitrogen, thus lead to a decrease in the microbial population and biomass. The same reason best explains the fact that higher BTN helps compensate for and mitigate the immobilization impact of higher BTC, increases soil nitrogen availability, and improves SMBC. In contrast, the results of another meta-analysis conducted by Chagas et al. (2022) showed that despite the absence of any significant variability among the different levels of BTC there was an increase in the SMBC with higher BTC. Our results demonstrated that BPH more than 8 significantly increased the SMBC, but the highest response was found at the BPH range of 8–9 (Liu et al. 2016b); we also noticed that BPH < 8 had no significant impact on the SMBC. On the other hand, Crombie et al. (2015) demonstrated that BPH below 7 had a more pronounced priming effect on soil carbon mineralization. Biochar ash content had an overall substantial positive impact on the SMBC, and the highest response was found when the ash content was > 400 g/kg. The high effect size of biochar with higher ash content suggests that this biochar is highly effective in promoting SMBC (Li et al. 2020b). This could be because higher BASH provides large amounts of minerals and nutrients in the soil, which enhances microbial growth (Lehmann et al. 2011; Deshoux et al. 2023). The high total surface area of biochar offers a larger surface area for microbial colonization, thereby promoting microbial biomass carbon (Hossain et al. 2020). Previous research has suggested that the incorporation of biochar can positively affect SMBC by supplying additional carbon and nutrients for soil microbes (Jeffery et al. 2011). The findings align with prior investigations indicating the beneficial impact of biochar on SMBC (Liu et al. 2017). Biochar application type and BAGE are also important factors that determine the positive impact of biochar on SMBC. The results from this study are consistent with previous research that the beneficial impacts of biochar decreased with the biochar aging time (Zhou et al. 2017). The reason for less improvement in the SMBC with the increase in biochar aging time is due to changes in the biochar properties for a long time in the soil environment (Castaldi et al. 2011; Mukherjee et al. 2014; Rushimisha et al. 2023). A field study by Cooper et al. (2020) found the highest SPH in the first 2 years of the experiment, followed by a decline in the SPH with the biochar application in the subsequent years. Repeated biochar application rather than a single application provides additional dissolved organic carbon and energy sources for microbial activities (Shi et al. 2021). Other long-term field studies also observed no change or even less microbial activity due to aged biochar in treatment plots. This could be associated with increased microbial activities with the freshly applied biochar for a short time period (Cheng et al. 2006), due to its easily mineralizable organic content (Lehmann et al. 2011; Woolf and Lehmann 2012; Domene et al. 2014). The mechanisms for increased SMBC during BAGE 25–36 months in our study are unknown, but this trend is probably due to the biochar application rates, the management practices, and climatic and soil conditions of the field experiments. Wu et al. (2018) noticed similar results with 40 t/ha of fresh biochar and the same amount of 3-year field-aged biochar along with additional urea application in both treatments, nosignificant differences were detected among fresh and aged biochar treatments on SMBC. Aged biochar is rich in stable organic carbon by the sorption of dissolved organics and the formation of micro-aggregates onto charcoal particles, which makes it persistent in soils for a longer time period (Heitkötter and Marschner 2015; Wang et al. 2016; Wang et al. 2017) and increase soil microbial activity and structure (Quilliam et al. 2013). Furthermore, Sun et al. (2016) suggested that 34 months aged biochar in the soil greatly promotes bacterial activities. The contrasting results in this study suggested the importance of noting that the effect of biochar on SMBC may also depend on other factors, such as biochar feedstock types, application rate, type and age, and pyrolysis temperature (Spokas and Reicosky 2009; Lehmann et al. 2011; Cai et al. 2021). The variability in the impacts of biochar on SMBC may also depend on other important fundamental properties, such as functional groups involving oxygen or nitrogen, porosity, electron transfer capacity, etc. (Rushimisha et al. 2024). Future research should include these properties to further the current understanding of biochar impacts on SMBC. Further investigations are also required to study the interactive effects of biochar and management practices (such as tillage, fertilization, and irrigation) on SMBC to optimize biochar application strategies for soil health improvement.

5 Conclusion

Our findings underscore the multifaceted nature of the relationship between biochar and SMBCacross different climates, soil types, and biochar properties. Soil texture, particularly clay content, could significantly influence the response of biochar application for SMBC enhancement. Among all the predictor variables, biochar properties play an important role in increasing SMBC. Fine and coarse-textured soils with varied pH levels, low STC, and STN, showed a significant increase in SMBC with the biochar application. Biochar impacts were more pronounced under climatic conditions where MAT was up to 15 °C, MAP range between 500-1000 mm, and upland land use types. Cotton and maize residue is significantly superior among various crop residue feedstock types. Repeated application and fresh biochar showed a significant increase in SMBC compared to the single application and aged biochar. Our results suggest that biochar produced at low pyrolysis temperatures and applied at low rates significantly enhances SMBC. We also found that biochar chemical properties such as low BTC and high BTN promote SMBC. The combined applications with other organic amendments and nitrogen fertilizer significantly improved the impacts of biochar, except for straw. Therefore, we call for carefully assessing climatic conditions, soil, and biochar characteristics before applying biochar as a sustainable management practice. This study also suggests adopting a holistic approach to soil management, including diversifying agricultural systems and using complementary practices, such as additional manure/compost and the required nitrogen fertilizer, to enhance biochar impacts. However, there is still uncertainty about the synergistic effects of biochar application with other organic amendments on the variations in SMBC, which needs further investigation as more observations and measurements are available. Our study explored maximizing the benefits of biochar application and provided science-based information for related decision-making, tailored field practices, and further research efforts.

Supplementary Information

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Additional file 1.

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Author contributions
Yogesh Kumar: Conceptualization, Formal analysis, Investigation, Writing—Original Draft. Wei Ren: Conceptualization, Supervision, Funding acquisition, Writing—Review & Editing. Bo Tao: Writing—Review & Editing. Haiying Tao: Writing—Review & Editing. Laura Lindsey: Funding acquisition, Writing—Review & Editing.

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

Author details
[1]Department of Natural Resources and the Environment, University of Connecticut, Storrs, CT 06269, USA. [2]Department of Plant Science and Landscape Architecture, University of Connecticut, Storrs, CT 06269, USA. [3]Horticulture and Crop Science, The Ohio State University, 2021 Coffey Road, Columbus, OH 43210, USA.

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