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Research article

Combining meta-analysis and local assessment: An in-depth approach on biochar use towards soil carbon sequestration

Jhon Kenedy Moura Chagas, Cícero Célio de Figueiredo *

Faculdade de Agronomia e Medicina Veterinária, Universidade de Brasília, Brasília, DF, Brazil

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ABSTRACT

This study evaluates the impact of biochar, produced by valorizing waste sewage sludge, on soil carbon (C) sequestration, combining a global meta-analysis with a four-year tropical field trial. Biochar application can enhance soil C and mitigate climate change, contributing to sustainable resource management. The meta-analysis of 586 paired comparisons from 169 studies showed increases in total C (TC) and various soil C fractions post-biochar application. In order to compare global results with local data, the effects of sewage sludge biochar (SSB) obtained at contrasting temperatures were evaluated in a field experiment conducted over five years. The field trial using SSB pyrolyzed at 300°C (SSB300) and 500°C (SSB500) showed modest TC increases (7.7 % with SSB300, 0.7 % with SSB500) and minimal changes in other C fractions. Importantly, the absolute TC gain with SSB300 surpassed those from practices like no-till farming. These results underscore the need to tailor biochar applications and optimize pyrolysis conditions to local settings to improve soil C sequestration. Adopting such context-specific strategies can enhance waste recycling, promote sustainable agriculture, and aid in climate change mitigation.

1. Introduction

Managing soil carbon (C) pools is essential for improving soil health and mitigating climate change [35]. Several agricultural practices contribute to increasing soil C pools and sequestration, including no-till farming [14], cover cropping [51], integrated crop-livestock-forest systems [15], reforestation with planted forests [59], manure application [27], and biochar use [26].

Biochar, a C-rich material produced by pyrolysis of organic biomass under low-oxygen conditions, has gained attention for its potential to improve soil C fractions, enhance soil fertility, and reduce greenhouse gas emissions [2,40]. Biochar can increase labile and stable soil organic C fractions, including total C (TC), easily oxidizable organic C (EOOC), permanganate oxidizable C (POXC), fulvic acids (FA), humic acids (HA), and humin [31,66]. Understanding how biochar affects these different C fractions is crucial for optimizing its use in soil C management strategies.

Despite these benefits, the effects of biochar are highly variable, influenced by factors such as feedstock type, pyrolysis conditions, application rates, soil type, and climate [25,32,39,41]. For instance, chemical properties such as pH, cation exchange capacity (CEC), electrical conductivity and liming value are affected by the type of raw material and the pyrolysis temperature [19]. [48] evaluated the properties of biochars produced from 20 different organic wastes. In this study, the authors reported wide variations in the contents of phosphorus (0.04–37.54 g kg^{-1}), nitrogen (3.9–28.8 g kg^{-1}), C (261–655 g kg^{-1}), ash (1.2–51.2 %), and CEC (7.2–200 $cmol_c$ kg^{-1}). The carbon stability of biochar produced using a mixed woody and grass biomass was around four times higher compared to the biochar produced using sewage sludge biomass [1]. Furthermore, the greenhouse gas mitigation potential of biochar varies according to the type of feedstock and pyrolysis temperature [67]. This variability makes it challenging to predict consistent outcomes of biochar application across different environments, emphasizing the need for approaches combining global meta-analytical insights and localized field data.

Global meta-analyses provide aggregated data on the effects of biochar on soil C pools, showing general trends like increases in various soil C fractions [12,44,7]. For instance, [12] reported significant increases in TC, EOOC, microbial biomass C, and FA following biochar application. However, these analyses often mask significant site-specific variations due to differing environmental conditions and management practices [58]. The effects of biochar on other soil C fractions, such as dissolved organic C, humic acid, and humin, are less predictable, underscoring the

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* Corresponding author.
E-mail address: cicerocf@unb.br (C.C. Figueiredo).

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complex interactions between biochar properties and environmental factors [12].

Subgroup analyses within meta-analyses help to refine understanding by isolating effects under specific conditions, providing more targeted insights for guiding biochar application in diverse settings [10]. For example, biochar produced from different feedstocks can have varying impacts on soil C fractions due to differences in their chemical composition and stability [44].

Local field trials are essential for understanding how biochar affects different soil C fractions and crop productivity under specific environmental conditions. Field studies have shown that biochar application can significantly increase stable soil C fractions like humic substances, while effects on labile fractions may vary [17,42]. A field study in Brazil using sewage sludge biochar (SSB) reported increases in stable soil C fractions, such as non-oxidizable organic C, but showed varied effects on more labile fractions and overall soil fertility, highlighting the influence of local soil properties and climate. These findings highlight the importance of localized data to validate or challenge global findings to ensure that biochar use is both effective and context-specific.

Comparing results from global meta-analyses with local studies is particularly relevant in countries like Brazil, which have a high potential for biochar use due to their large agricultural sector and diverse climatic conditions [38,4]. Despite this potential, there are few long-term studies on the effects of biochar in tropical regions, leading to a knowledge gap about its sustained impact under local conditions. Moreover, the accelerated expansion of the global C credit market [68] could benefit from reliable data on the efficacy of biochar, aiding the development of verified C standards and methodologies, such as those promoted by Verra [63]. Aligning local field trial results with global meta-analyses can enhance the accuracy of C credit metrics and promote sustainable agricultural practices. Furthermore, since sewage sludge biochar has a lower carbon content compared to other biochars, its impact on C buildup in tropical soils may differ completely from that of C-rich biochars applied in temperate regions. In this regard, comparing local field experiments with global meta-analyses is essential for understanding the limitations and potential of a specific biochar for soil C sequestration. Additionally, by comparing local results with those available globally, this type of approach helps reduce the need for multiple experiments, lowering costs and broadening the scope of conclusions.

This comparative analysis is crucial for providing evidence-based recommendations on biochar use, potentially influencing policy and market decisions regarding C credits. By aligning global evidence with local findings, this study aims to clarify the conditions under which biochar is most effective, contributing to the broader goal of enhancing soil health and mitigating climate change through optimized soil management practices.

This study aimed to integrate insights on the effects of biochar on soil C pools from global and local perspectives. By comparing global meta-analyses data with local field trials results, this research comprehensively analyzes biochar use for soil C management, supporting more effective and sustainable agricultural practices. Specifically, this study presents, for the first time, evidence on the limitations of using sewage sludge biochar for carbon sequestration under specific tropical soil conditions.

2. Material and methods

2.1. *Data sources and selection process*

The global meta-analysis results used in this study were derived from a comprehensive dataset that included 586 paired comparisons from 169 peer-reviewed articles reported in our previous study [12]. Fig. 1 shows the procedures adopted in the search and selection of articles. These articles were selected based on stringent criteria, such as randomized experimental designs, explicit replication numbers, control and treatment consistency, and clear evaluation of at least one soil C fraction using defined determination methods. Data extraction focused on key variables, including mean values, standard deviations, and the number of repetitions for various soil C fractions – total C (TC), easily oxidizable organic C (EOOC), permanganate oxidizable C (POXC), fulvic acid (FA), humic acid (HA), and humin. The data were categorized based on key factors such as biochar feedstock, pyrolysis temperature, application rate, soil C content, experiment type, and duration. A random-effects model was utilized to calculate the response ratios, expressed as log-transformed ratios of means, to quantify effect sizes across studies. Statistical significance was determined using 95 % confidence intervals, and results were expressed as percent changes to evaluate the effectiveness of biochar in enhancing soil C pools globally.

The local field trial data were collected from an experiment conducted at Fazenda Água Limpa (FAL/UnB), Brasília-DF, Brazil, over seven growing seasons (2015–2021). The experimental area is located at latitude 15°56′45″ S, longitude 47°55′43″ W and an elevation of 1095 m. The region's climate is classified as tropical savanna (Aw, Köppen). The average annual precipitation is 1400 mm and the average annual temperature ranges from 14.7 to 25.4 °C. The soil was classified as Latossolo Vermelho-Amarelo according to the Brazilian Soil Classification [57], clayey Oxisol (Typic Haplustox) [60], Gibbsic Ferralsol [30]. The field trial specifically examined the effects of SSB produced at two pyrolysis temperatures, 300°C (SSB300) and 500°C (SSB500). Treatments included a non-fertilized control (no biochar, no mineral fertilization), SSB300 and SSB500 applications, with four repetitions. Biochars were applied at 0.75 % (w/w) during the initial two growing seasons and

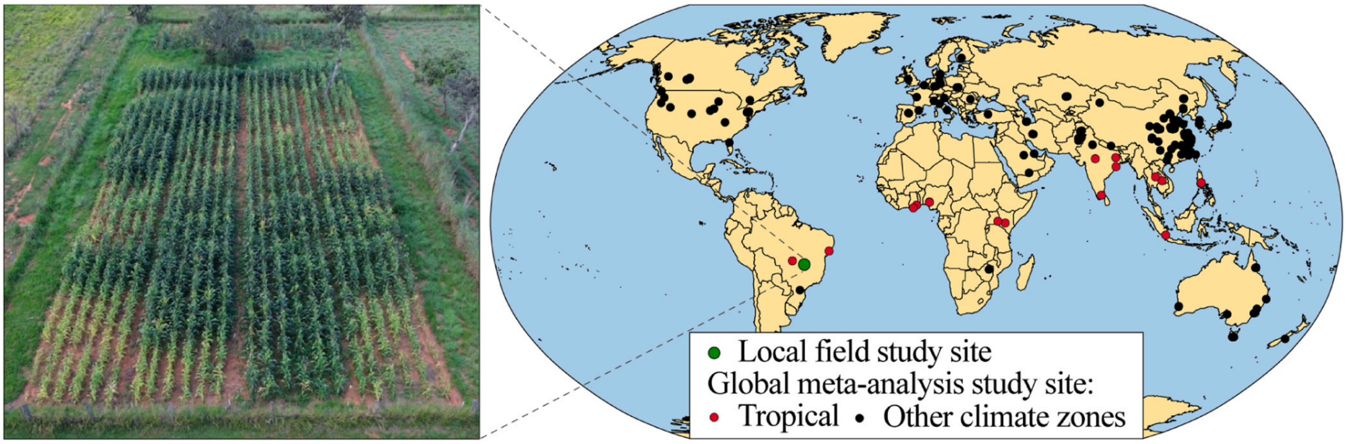

Fig. 1. Global meta-analysis and local field trial sites for assessing soil carbon changes due to biochar amendment. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

incorporated into the soil's top 0.2 m layer. The value of 0.75 % (w/w) was obtained considering a biochar application rate of 15 Mg ha^{-1} in the 0–0.20 m soil layer and a soil density of 1 Mg m^{-3} . The application rate of 15 Mg ha^{-1} followed recommendations from Jeffery et al. [32] and Zhang et al. [72], which suggested that rates of 10–20 Mg ha^{-1} could improve crop productivity while considering agronomic costs. The study focused on the first four seasons (2015–2018) to capture the direct effects of biochar amendments, as previous research indicates that the impact of biochar on soil properties often manifests one to two years post-application [11]. The same soil C fractions assessed in the global meta-analysis were measured in this local study to ensure consistency and comparability between the datasets. After harvesting (in June), the 0–0.20 m soil layer was sampled with a Dutch auger in each growing season. Five subsamples per plot were collected and mixed to obtain a composite sample. TC was determined using a CHN elemental analyzer (Eurovector EA3000, Milan, Italy) at 980°C. EOOC was measured by wet oxidation with potassium dichromate without external heating [64], and POXC by oxidation with potassium permanganate [8]. Soil humic substances were fractionated into FA, HA, and humin based on solubility differences in acidic and alkaline media [61], adapted from [6]. The C content of these fractions was quantified by oxidation with potassium permanganate.

2.2. Analytical approaches for data integration and comparison

The soil C fractions common to both studies (TC, EOOC, POXC, FA, HA, and humin) were identified and analyzed to integrate and compare the global meta-analysis with the local field trial data. However, subgroup analyses were only performed for TC and EOOC due to the availability of sufficient data in the meta-analysis. For the other soil C fractions (POXC, FA, HA, and humin) only overall effect sizes were calculated because the dataset did not support a more detailed subgroup analysis. The comparison focused on the overall effect sizes and specific subgroups matching the local field trial conditions. This methodology aligns with the concept of dynamic scoping as outlined by [58], where subsets of the global dataset are filtered to match local conditions, thereby enhancing the relevance and applicability of the findings. This approach allows for a detailed examination of the effects of biochar on soil C pools observed globally compared to those found locally.

The local data were transformed into percent changes relative to the control treatment, based on mean values across the first four growing seasons, facilitating a direct comparison with the global dataset. The analysis involved calculating the mean, standard error of the mean (SEM), 95 % confidence intervals (CI), and percent change relative to the control for each soil fraction. The 95 % CI for each treatment was calculated using Eq. (1):

$$CI_{95} = SEM \times t_{(0.975,N-1)} \tag{1}$$

where $t_{(0.975,N-1)}$ is the critical value from the t-distribution for a 95 % confidence level with $N - 1$ ° of freedom. The percent change (Pc) relative to the control was determined using Eq. (2).

$$P_C = \left(\frac{Mean_{treatment} - Mean_{control}}{Mean_{control}}\right) \times 100 \tag{2}$$

To estimate the variability of the Pc, the confidence interval for the percent change (CI_{PC}) was calculated using Eq. (3).

$$CI_{PC} = \left(\frac{CI_{95}}{Mean_{control}}\right) \times 100 \tag{3}$$

The confidence intervals were also used to statistically compare the effect sizes between the field trial and the meta-analysis. If the confidence intervals of the percent change from the field trial and the meta-analysis overlapped, no significant difference was suggested. This statistical approach provided a standardized method for quantifying differences between the global and local datasets, enabling a comprehensive understanding of the effects of biochar on soil carbon sequestration in various contexts. The statistical analyses were conducted using Python with appropriate statistical libraries [52].

3. Results and discussion

3.1. A comparison of local field trial and global meta-analysis parameters

The parameters of the local field trial were categorized according to the global meta-analysis framework to ensure comparability, revealing several key differences (Table 1). The local study utilized SSB produced at 300°C and 500°C, classified as low and medium temperature, respectively, according to the meta-analysis study [12]. This classification is similar to that presented by [67]. Biochar C contents applied in the local study were considered low [12]. The comparatively low C content of SSB stems from its elevated ash and mineral content, which reduces the proportion of organic C. This contrasts with lignocellulosic biomass feedstocks, which have lower ash content, enabling higher C concentrations [21,45]. The local field trial where biochar was applied presented fine-textured soil with a high initial soil C content located in a typically tropical region. These characteristics were underrepresented in the meta-analysis, with fewer than one-third of the global studies investigating similar conditions. This discrepancy underscores the variability in biochar types and environmental conditions studied globally, which can affect the overall trends.

The low representation of SSB in the meta-analysis dataset, comprising only 11 % of the studies, reveals a significant gap in research. Despite its limited coverage, SSB remains a valuable input in sustainable agriculture, offering improvements in soil fertility [62], C sequestration [70], and reductions in greenhouse gas emissions [29]. Its distinct properties, including pathogen reduction, nutrient provision, and heavy metal stabilization, position it as a promising alternative to traditional waste disposal methods, especially in tropical regions [11, 13]. Given the potential environmental and agricultural benefits of SSB, further research is necessary, particularly in underrepresented tropical environments, to optimize its use across different agroecological contexts [23].

Tropical regions, which accounted for only 12 % of the studies in the global meta-analysis, are particularly underrepresented (Fig. 1). This is significant because tropical soils and climates, characterized by rapid organic matter turnover and unique microbial dynamics [56], influence biochar's interaction with soil differently from temperate regions. These conditions present distinctive challenges and opportunities for C sequestration. Given that tropical regions occupy 40 % of the Earth's surface and face substantial agricultural constraints, biochar –

Table 1
Comparison of local field trial parameters with meta-analysis classifications and study distribution.

Parameter	Field trial value	Meta-analysis classification	% of studies in meta-analysis
Raw material	Sewage sludge	Sewage sludge	11 %
Pyrolysis temperature (°C)	300	Low	14 %
	500	Medium	76 %
Biochar C content (%)	23.4 (SSB300)	≤ 35 %	14 %
	19.0 (SSB500)	≤ 35 %	14 %
Biochar rate (%)	0.75	Low	56 %
Soil texture	Silty clay	Fine	23 %
Soil pH	4.9	Acid	54 %
Soil C content (%)	2.64	High	26 %
Climate zone	-	Tropical	12 %
Experiment type	-	Field trial	54 %
Experiment duration	7 years	> 2 years	31 %

particularly SSB – could play a crucial role as a tool for C sequestration and soil enhancement. However, more extensive field trials and long-term studies are required to assess the potential impact of SSB in these regions.

Comparing our local study to biochar applications in other regions of Brazil reveals notable differences in both application rates and biochar characteristics that influence soil C results. [37] applied wood biochar at 2 %, a dose twice as high as that applied in our field experiment (0.75 %), resulting in a 24.6 % increase in total soil C compared to 7.7 % locally. In a tropical region of Brazil, [50] demonstrated a dose-dependent effect, with higher doses (0.5 % and 1.1 %) resulting in increases of 12.1–17.5 %, while a lower dose (0.3 %) produced a similar effect to our local study. The higher C content in lignocellulosic biochars (approximately 50 %) compared to SSB (19–23.4 %) further explains these divergent results, emphasizing the critical influence of feedstock and pyrolysis conditions on soil C sequestration.

When compared to studies conducted in China, similarities in the economic context and generally low organic nature of biosolids are offset by significant differences in experimental conditions and results. The C content of sewage sludge produced in China is similar to that presented in the present study [43]. Despite this, in China, most experiments were short-term pot trials with SSB application rates ranging from 2 % to 10 % [33,65], while the only field trial [71] evaluated moderate doses (0.5–1.4 %) on sandy soils with low initial C content ($\leq$1 %), achieving relatively larger percentage increases in soil C. In comparison, the local Brazilian field trial applied SSB at a conservative rate of 0.75 % to fine-textured soils with a higher baseline total C content. Although the overall C content in Chinese SSB (11.3–28 %) is broadly comparable to that in the Brazilian study, the divergent experimental designs—particularly the higher application rates in Chinese pot trials versus the more realistic, field-relevant conditions in Brazil—suggest that the observed differences in soil C sequestration are as much a function of methodological variance as they are of feedstock properties.

3.2. Comparative analysis for total carbon (TC)

Considerable differences in the TC values emerged between the global meta-analysis and the local field trial. The meta-analysis revealed a significant positive impact of biochar on TC across various contexts, with percent increases ranging from 28.9 % to 64.3 % (Fig. 2). However, the local trial with SSB showed more modest gains, with TC increasing by 7.7 % for SSB300 and only 0.7 % for SSB500. Although the TC increase for SSB500 was not statistically significant, as its confidence interval overlapped zero, there was no significant difference in percent change between SSB300 and SSB500. This discrepancy highlights the importance of considering local soil and environmental conditions when interpreting global data, especially in tropical soils. The temporal dynamics of TC over the four years in the local trial are presented in Fig. S2a.

Overall, the smaller TC responses in the tropical field trial compared to the global meta-analysis can be interpreted as the combined result of (i) limited representation of SSB and tropical, high-C soils in the global dataset, (ii) the lower and field-realistic application rate used locally, and (iii) the lower C content and stability typically associated with SSB [1,12,45,49]. In addition, the inherent complexity of in situ tropical field conditions may further constrain the persistence of added C relative to controlled experiments, contributing to the divergence between global and local effect sizes [69]. The following paragraphs explore these interacting factors in the context of SSB traits and tropical soil conditions.

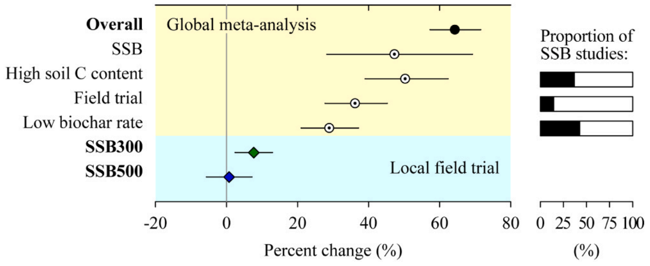

Fig. 2. Percent change in soil total carbon (C) from global meta-analysis and local field trial and proportion of SSB studies for specific conditions. SSB: sewage sludge biochar pyrolyzed under 300°C (SSB300) and 500°C (SSB500).

First, SSB and soils with high initial C content are underrepresented in global datasets, as mentioned in Section 3.1. These conditions reduced the overall effect size in TC increases. Field trials and studies using low biochar application rates are prevalent in the global dataset, accounting for over 50 % of the cases (Table 1). However, among studies specifically using SSB, the proportion of field trials drops to 14.3 %, and only 42.4 % of studies employed low SSB application rates (Fig. 2). This suggests that the global meta-analyses for SSB are predominantly based on controlled environments and higher application rates, which may overstate the TC increases compared to what is achievable under field conditions with lower application rates. Consequently, the global meta-analyses may not accurately reflect the performance of SSB under practical field conditions, potentially biasing the overall TC change.

High initial soil C content likely constrained the observed percent increases in the local trial. Soils with higher baseline C levels require more substantial C input to register noticeable percent changes [49]. Additionally, field trials tend to present lower TC increases due to the complexity of *in situ* conditions. Unlike controlled laboratory experiments, field trials expose biochar to various dynamic environmental disturbances, such as tillage, fluctuating temperature, water availability, redox cycles, and biotic activities [69]. These factors contribute to reduced effect sizes in field settings, as biochar particles experience greater physical and chemical stress, limiting their stability and C sequestration potential over time.

According to the meta-analysis, the biochar application rate is the primary factor influencing TC increases [12], with higher TC increases observed at higher biochar rates. The mean application rate in the meta-analysis studies assessing TC was 2.90 %, which is almost three times higher than the 0.75 % used in the local trial. This difference in biochar application rates likely contributes to the discrepancy between global and local results.

SSB, particularly when pyrolyzed at low to medium temperatures, is known for its nutrient supply capacity [24]. However, SSB typically has a lower C content and stability compared to other biochars, limiting its long-term C sequestration potential. This is attributed to its higher O/C ratios, lower recalcitrance indices, and higher ash content [1,45]. These factors reduce its effectiveness in maintaining soil C stocks over time, as observed in the local field trial.

Notably, the meta-analysis included no SSB results lasting more than two years, and only 5.7 % of SSB results were obtained in tropical regions. Optimizing pyrolysis conditions to produce more recalcitrant biochar is crucial to enhance the C sequestration potential of SSB in the tropics. Co-pyrolysis of SSB with plant materials has shown a potential to increase the C content and improve stability [46]. Co-pyrolysis with organic additives has been shown to reduce the H/C, N/C, and O/C ratios, thereby improving long-term SSB stability [70].

Despite the lower percent increases observed in the local trial, the absolute increases in TC were substantial when compared to other agricultural management practices. Over the 4-year period, the average increases in TC corresponded to 4.19 Mg C ha^{-1} for SSB300 and 0.40 Mg C ha^{-1} for SSB500. For instance, after 31 years of cultivation, reductions in C emissions under no-till corresponded to a linear rate of 0.35 Mg C ha^{-1} year^{-1} compared to conventional tillage [22], amounting to an increase of 1.4 Mg C ha^{-1} over 4 years. Similarly, meta-analyses report positive effects of cover crops on SOC stocks with average SOC accrual rates of 0.21–0.56 Mg C ha^{-1} year^{-1} [53], corresponding to an increase of

0.84–2.24 Mg C ha^{-1} over 4 years. Thus, the absolute increase in TC with SSB300 surpasses those achieved with no-till and cover crop adoption over a similar period. However, direct comparisons should be made cautiously due to differences in study durations and conditions.

Although the percent increase in TC with SSB300 (7.7 %) was lower than the global average for biochar (64.3 %), it is comparable to the percent increases observed for other widely recognized soil management practices that contribute to C sequestration and climate change mitigation, such as no/reduced tillage (5.0 %) and cover crops (11.6 %) [5]. This indicates that, in absolute terms, the application of SSB can be an effective strategy for increasing soil C stocks, even if the percent increases appear modest compared to global averages for biochar.

It is worth noting that biochar was only applied in the first two growing seasons of the local trial, yet the cumulative increase in TC over four years was substantial (Fig. S2a). While the intention is not to propose replacing established practices like no-till farming or cover cropping with biochar application, these findings suggest that combined technologies could contribute synergistically to increasing soil C stocks. However, further long-term field studies are needed to confirm this hypothesis and to understand the interactions between biochar application and other soil management practices.

By adjusting biochar production and application strategies to match local environmental conditions, stakeholders can ensure that biochar projects contribute meaningfully to C sequestration efforts, particularly in regions like Brazil, where tropical soils present unique challenges and opportunities for C management. Contextualized biochar use can also support C credit markets, allowing for more accurate accounting of verifiable climate benefits.

3.3. *Comparative analysis for easily oxidizable organic carbon (EOOC)*

The global meta-analysis indicated a significant positive effect of biochar application on EOOC, with an overall percent increase of 84.3 % (Fig. 3). Notably, SSB exhibited an even larger effect, showing a percent increase of 242.3 %. In contrast, the local field trial demonstrated a modest increase in EOOC for SSB300 (4.7 %) and a non-significant decrease for SSB500 (–1.8 %). No significant difference was observed between the SSB300 and SSB500 treatments, suggesting that pyrolysis temperature may not substantially impact EOOC under the conditions of the local field trial. The temporal dynamics of EOOC in the field trial is presented in Fig. S2b.

The pronounced discrepancy between the global meta-analysis and the local field trial suggests that the large positive effects of SSB on EOOC observed globally may be overestimated due to the predominance of laboratory studies in the meta-analysis dataset. The meta-analysis primarily comprises laboratory studies, with only 11.8 % of SSB studies conducted under field conditions and an equal proportion on soils with high initial C content (Fig. 3). Although a higher proportion of SSB studies used low biochar application rates, this still represents less than one-third of the studies. This confirms the scarcity of SSB studies assessing not only TC but also EOOC under field conditions. Moreover, no experiments longer than two years were included in the SSB meta-analysis dataset, highlighting a gap in long-term field studies on the effects of SSB biochars on EOOC.

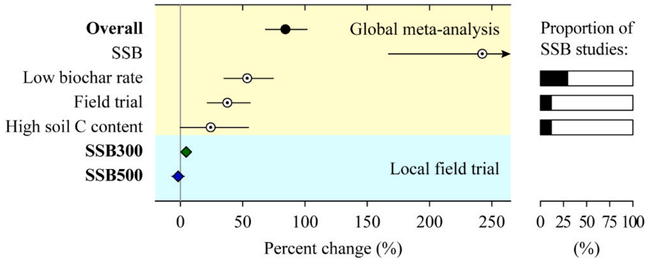

Fig. 3. Percent change in soil easily oxidizable organic carbon (C) from global meta-analysis and local field trial and proportion of SSB studies for specific conditions. SSB: sewage sludge biochar pyrolyzed under 300°C (SSB300) and 500°C (SSB500).

Underrepresentation of specific conditions or subgroups in meta-analyses can bias effect size estimates and limit the generalizability of the findings [18]. The positive effects of SSB biochar on EOOC observed in laboratory settings may not directly translate to field conditions, especially in tropical soils.

Soil microbial dynamics influenced by biochar additions can also affect EOOC levels. Biochar can alter soil microbial community composition and activity [16], impacting the decomposition of organic matter and the turnover of labile C fractions [17]. The specific microbial environment in the local trial's tropical soil may differ from those in temperate soils [47] commonly studied in the meta-analysis, leading to varying effects on EOOC.

From an agronomic perspective, the lack of a significant increase in EOOC in the local trial suggests that the immediate benefits of biochar application on soil fertility through increases in EOOC could be context-dependent. EOOC is crucial for nutrient cycling and availability, directly influencing plant growth and yield [36]. These results affect soil organic matter dynamics, indicating that biochar may contribute more to stable C pools than labile ones in high-C tropical soils. This shift can influence the turnover rates of soil organic matter, potentially affecting long-term soil fertility and C sequestration strategies [34].

3.4. *Comparative analysis for other soil carbon fractions*

The effects of biochar on various soil C fractions differed between the global meta-analysis and the local field trial (Fig. 4), emphasizing the importance of biochar properties and site-specific conditions in soil C dynamics.

The global meta-analysis indicated significant increases in labile C pools, with a 22.9 % increase in POXC and a 42.1 % increase in FA following biochar application. These fractions are crucial for microbial activity and nutrient cycling, serving as indicators of soil health and fertility [73,9]. In contrast, the local field trial showed non-significant changes in both POXC and FA, with percent increases of 3.30 % and 3.97 % for SSB300, and 2.27 % and a slight decrease of 2.21 % for SSB500, respectively. The temporal dynamics depicted in Fig. S2c andS2d illustrate that these fractions remained relatively stable over the four years. The coherence in results between these two labile pools suggests that the methods of C determination yielded consistent trends,

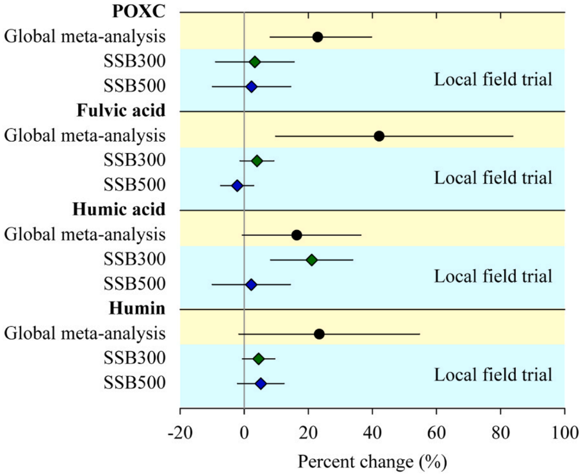

Fig. 4. Percent change in soil permanganate-oxidizable carbon (POXC), fulvic acid, humic acid, and humin from global meta-analysis and local field trial. SSB300 and SSB500: sewage sludge biochar pyrolyzed under 300°C and 500°C, respectively.

regardless of whether POXC or FA was measured. This insensitivity likely stems from the high native C content of the tropical soil (2.64 %), which masks the relatively small contribution of the low biochar dose (0.75 %) to these labile pools [49]. Additionally, the rapid turnover of labile organic matter characteristic of tropical environments [56] prevents the sustained accumulation of POXC and FA, contrasting with the clearer signals often observed in lower-C soils or controlled conditions dominant in the meta-analysis. Consequently, in high-C tropical soils, the contribution of SSB may be directed toward more stable C pools over the long term, rather than inducing immediate shifts in labile fractions, a hypothesis supported by the observed positive (though non-significant) trend in humin. This finding aligns with observations by [54], who reported a decrease in POXC after 12 months of biochar application.

For HA, representing the intermediate soil C pool important for soil structure and nutrient retention [3], the global meta-analysis suggested a moderate increase of 16.4 %. The local trial demonstrated a significant increase of 21.03 % with SSB300, while SSB500 showed a minor increase of 2.17 %. Similarly, a previous study with corn cob biochar reported a stronger effect on HA compared to FA [2], supporting the observation that certain biochars enhance HA more than FA.

This enhancement with SSB300 highlights that lower pyrolysis temperatures favor the retention of labile compounds, promoting humification. Lower temperatures (300–400°C) increase dissolved organic matter release, facilitating the transformation into humic substances due to higher oxygen-containing functional groups [20,55]. In contrast, higher pyrolysis temperatures (500–600°C) lead to greater carbonization, forming more recalcitrant C structures with lower O/C and H/C ratios and reduced labile components like protein-like substances, limiting availability for humification [20]. This underscores the importance of optimizing pyrolysis conditions to tailor biochar for specific soil management objectives.

Regarding humin, the most recalcitrant soil C fraction with turnover times from decades to centuries [28], both the meta-analysis and local trial showed non-significant changes despite the meta-analysis reporting a 23.4 % increase. The local trial observed modest increases of 4.47 % for SSB300 and 5.15 % for SSB500. These non-significant changes suggest that biochar's contribution to the most stable C pools may require higher application rates or longer periods to become significant. Additionally, the relatively low pyrolysis temperatures and low fixed C content of the SSB (3.03–5.47 %) likely limited their potential contribution to soil humin.

These varying effects of biochar on different C fractions have essential implications for soil C dynamics and management strategies. As observed with HA in the local trial using SSB300, the enhancement of intermediate C pools can improve soil structure and nutrient retention, contributing to soil fertility and resilience. Although the limited effect on labile C pools suggests that biochar may contribute more to stable C pools in tropical soils with high C content, this was not confirmed by the results for humin.

Therefore, tailoring biochar characteristics, such as feedstock selection and pyrolysis conditions, can optimize its effectiveness to match specific soil needs. Producing biochar at lower pyrolysis temperatures may enhance its ability to increase intermediate C fractions like HA. However, this must be balanced with the need for long-term stability, as lower temperature biochars may be less recalcitrant. These findings emphasize the necessity of considering biochar production parameters and site-specific factors to improve soil C sequestration and fertility through SSB application.

4. Conclusion

This study underscores the importance of integrating global meta-analytical insights with local field data to understand biochar's effects on soil C pools. While global meta-analysis showed positive impacts of biochar on TC and various soil C fractions, our local field trial using SSB in a tropical soil with high initial C content revealed more modest TC increases and minimal changes in other C fractions. These discrepancies highlight the necessity of considering local soil and environmental conditions when applying global findings. Despite lower percent increases, the absolute TC increase achieved with SSB300 was substantial compared to sustainable practices like no-till farming and cover cropping, indicating that SSB can still effectively enhance soil C stocks in tropical regions. Tailoring biochar production and application to local conditions, such as optimizing pyrolysis temperatures and exploring co-pyrolysis with plant materials, can enhance its effectiveness. Our findings have important implications for sustainable agriculture and climate change mitigation. Policymakers and stakeholders should consider local conditions and biochar properties to ensure meaningful contributions to soil health and climate goals. Future research should expand studies in tropical regions, conduct long-term field trials, and explore methods to improve biochar properties.

CRediT authorship contribution statement

Jhon Kenedy Moura Chagas: Conceptualization, Formal analysis, Writing; Cícero Célio de Figueiredo: Conceptualization, Writing Reviewing and Editing

Declaration of Competing Interest

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

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.nxsust.2025.100243.

Data Availability

Data of this research will be available on reasonable request.

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