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Meta-analysis reveals the effect of biochar on sulfonamides and tetracyclines in soil

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Sulfonamides (SAs) and tetracyclines (TCs) are widely used as broad-spectrum antibiotics, raising global concern due to their potential to accumulate in soil and consequent impact on the ecosystem. Although biochar has the ability to reduce SAs and TCs in soil, the understanding of the factors affecting the efficacy of biochar remediation remains inadequate. Here, a meta-analysis was conducted to evaluate the effects of biochar on SAs and TCs concentrations, soil properties, and microbial diversity in soils contaminated with antibiotics. The incorporation of biochar resulted in a marked decrease in the concentrations of SAs and TCs in soil, by 55.8% and 20.9%, respectively. In biochar-amended soil, the soil properties were enhanced, with notable increases of 3.2% in *pH* and 36.5% in organic matter, respectively. This further enhanced soil microbial diversity, with notable increases observed in both the Chao index (19.8%) and the Shannon index (6.9%). Additionally, agricultural waste biochar pyrolyzed at 300–500 °C demonstrated superior efficiency in reducing SAs and TCs. Furthermore, the remediation efficiency increased with higher soil *pH* and longer application time. The results of this research provided strong evidence for the remediation of soil antibiotic contamination.

Keywords Organic pollutant, Soil amendment, Risk assessment, Modification

As agriculture and pharmaceutical industries rapidly advance, antibiotic contamination has become an urgent problem[1]. Sulfonamides (SAs) and tetracyclines (TCs), two relatively common types of antibiotics, can enter the food chain, threatening both soil ecosystems and human health[2]. Drenching, ionic resins, biological treatments, and chemical oxidation have been used to eliminate antibiotics from soil[3]. However, these techniques present several critical limitations: potential secondary contamination, suboptimal efficiency, and the absence of an integrated and effective framework[4]. Therefore, a method is needed that is economical, efficient, and environmentally friendly for the remediation of antibiotic-contaminated soil.

Biochar is a carbon-dense solid product with significant potential for removing SAs and TCs from soil[5]. The effective removal of SAs and TCs by biochar is primarily attributed to its adsorption properties[6]. Previous studies have found that biochar adsorption of SAs and TCs from soil is primarily governed by electrostatic interactions, hydrogen bonding, hydrophobic interactions, $\pi - \pi$ electron donor − acceptor (EDA) interactions, and pore diffusion[7,8]. Normally, these adsorption mechanisms vary depending on the production conditions of biochar (feedstock, pyrolysis temperature, and time), which determine its physicochemical properties and thereby affect its ability to remove SAs and TCs from soil[9]. For example, biochar generated under higher pyrolysis temperatures and longer pyrolysis times typically contains a higher carbon content, which is associated with increased aromaticity, enhanced structural stability, and stronger π–π interactions, as well as being hydrophobic toward antibiotics[10]. In contrast, biochar with a high carbon content exhibits fewer surface functional groups, which affects ionic interactions[11]. However, most existing studies have been conducted under specific experimental conditions, which typically focus on a single factor and lacking systematic comparisons of variations in biochar types, application conditions, and soil environments. Such limitations restrict the generalizability of their findings for practical soil remediation[4,12].

Furthermore, the conditions under which the biochar was used also affected its removal of SAs and TCs[13]. During the long-term application of biochar, it inevitably undergoes aging, such as pore clogging, structural collapse, and enhanced surface polarity, which significantly influences its antibiotic removal efficiency[14]. Moreover, the antibiotic removal efficiency varies with different application rates of biochar, because biochar provides abundant adsorption sites[9]. A low application rate of biochar may result in inadequate adsorption sites for capturing all antibiotic molecules, thereby reducing the overall removal efficiency[15]. Therefore, a comprehensive analysis of how biochar application conditions influence its capacity to remove SAs and TCs

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is essential. In addition, the efficiency of SAs and TCs removal by biochar is also affected by soil properties[8]. Specifically, soil *pH* affects the speciation of SAs and TCs. In general, under high *pH* conditions, SAs and TCs molecules are negatively charged and form complexes with cations in the soil, which enhancing their adsorption and immobilization[16]. However, the combined effects of these factors remain poorly understood in previous studies, highlighting the need for more systematic and integrative research.

This study analyzed 44 articles by meta-analysis to evaluate the impact of biochar on SAs and TCs from soil. Further, the aims of this study were: (1) to assess the impact of biochar addition on the SAs and TCs in soil; (2) to investigate whether biochar influences the ecological remediation of antibiotics through changes in soil properties; and (3) to reveal the response of biochar to the remediation of antibiotic-contaminated soils under different production and application conditions. By integrating the results of multiple studies, the present study identifies the key factors that influence the removal of SAs and TCs by biochar, and provides novel insights into the strategic selection and application of biochar under diverse soil and environmental conditions.

Methodology and methods

Data collection

The data for this research were collected from peer-reviewed publications indexed in two databases: Web of Science and China National Knowledge Infrastructure. The study keywords used were: ((biochar OR char OR black carbon OR charcoal OR agchar) AND ("antibiotic" OR " sulfonamide∗" OR " tetracycline∗" OR "macrolide∗" OR "quinolone∗")). A diverse set of keywords was used to guarantee thorough coverage of the relevant literature for this meta-analysis. By June 30, 2025, a total of 2,889 papers were obtained. Subsequently, based on the titles and abstracts, 889 studies unrelated to soil antibiotic contamination were excluded. Initially, four stringent screening criteria were employed through a thorough review of abstracts and full texts: (1) the study examined how biochar influences antibiotic-contaminated soils, particularly with respect to SAs and TCs concentrations, soil properties, and soil microbial diversity; (2) sample sizes were clearly defined, and both experimental groups and selected variables were maintained under consistent conditions; and (3) essential information on soil type, experiment duration, and overall conditions was explicitly reported.

The final dataset consisted of 44 studies encompassing 1090 paired observations (the complete reference list is provided in the supplementary material). The PRISMA flowchart for selecting a paper is illustrated in Figure S1.

Data extraction and categorization

The following variables were extracted from the peer-reviewed papers: (1) Auxiliary variables: biochar (rate applied, feedstock, pyrolysis temperature, and pyrolysis residence time) and soil (type and texture). (2) Target variables: soil antibiotic (SAs and TCs), *pH*, soil organic matter (SOM), dissolved organic carbon (DOC), total organic carbon (TOC), and microbial diversity (the Shannon and Chao indices).

Data related to the target variables were directly obtained from tables in the selected articles. In addition, data presented as images were extracted using the GetData graphical digitizer software (http://getdata-graph-digitizer.com/). Duplicate numbers (n) and standard deviation (SD) were recorded for each study. The study reports standard errors (SE), which were transformed to SD using a specified equation. In research lacking SD or SE, SD was estimated as 1/10 of the mean[17].

Auxiliary variables were classified according to information obtained from peer-reviewed publications, allowing for effective comparison across studies. Biochar feedstocks were categorized into agricultural waste (wheat straw, rice straw, maize stubble, rice husk, rape straw, soybean straw, corn cobs, walnut shells, wheat bran, coconut shells, and sunflower husk), wooden material (sawdust, conifers, dried willow, pine woodchip, hardwood, wood, wood waste, and willow), green waste (bamboo, sugarcane, straw, coconut, miscanthus, and olive pomace). Pyrolysis temperatures for biochar production were categorized into three ranges: low (< 300 °C), medium (300–500 °C), and high (> 500 °C)[13]. The residence time for biochar pyrolysis was classified as short (< 1 h), medium (1–3 h), and long (> 3 h)[12]. Soil textures were grouped into three classes: fine (clay, silt clay, loamy clay, and sandy clay), medium (clay loam, loam, silty clay loam, silt, and silt loam), and coarse (sand, loamy sand, sandy loam, and sandy clay loam)[18]. Finally, the experiment duration was divided into three groups (< 30 d, 30–60 $\overline{X_C}$d, and > 60 d)[9].

Data analysis

In this study, the natural logarithmic response ratio (ln *RR*) was employed to assess how biochar influences selected variables. The ln *RR* effectively reduces biases associated with non-normal data, and the transformed data are generally consistent with a normal distribution[18]. We finally decided to use ln *RR* for this meta-analysis. The formulas are as follows:

$$\ln RR = \ln(\overline{X_T}/\overline{X_C}) = \ln\overline{X_T} - \ln\overline{X_C} \tag{1}$$

Where $\overline{X_T}$ and represent the average values of the selected variables under biochar treatment and control, respectively. The variance (v) of ln *RR* is calculated as follows:

$$v = \frac{S_T^2}{n_T\overline{X_T}} + \frac{S_C^2}{n_C\overline{X_C}} \tag{2}$$

where S_T and S_C are the standard deviations for the biochar treatment and control groups, respectively; n_T and n_C refer to the number of replicates in the respective groups.

The random-effect model incorporates both within-study variance (v_i) and between- study variance (τ^2[2]), and the weight factor (w_i) is calculated as follows:

$$w_\mathrm{i} = \frac{1}{v_i + \tau^2} \tag{3}$$

$$RR_{++} = \frac{\sum_{\mathrm{i}=1}^{m} w_i \ln RR}{\sum_{\mathrm{i}=1}^{m} w_i} \tag{4}$$

where *i* denotes the total number of observations.

The 95% confidence interval (95% CI) for each variable was estimated using the following equation:

$$95\%CI = RR_{++} \pm 1.96SE(RR_{++}) \tag{5}$$

where $SE(RR_{++})$ was the standard error of the weighted response ratio (RR_{++}).

$$SE(RR_{++}) = \sqrt{\frac{1}{\sum_{\mathrm{i}=1}^{\mathrm{m}} w_i}} \tag{6}$$

If the 95% CI for the effect size of the variable included ‘0’, it indicated that the variable was minimally affected by biochar.

The percentage change of a variable was obtained by

$$(\mathrm{e}^{RR_{++}} - 1) \times 100\% \tag{7}$$

The RR_{++} of each variable was calculated using OpenMEE software (http://www.cebm.brown.edu/openmee/index.html).

The effects of biochar on antibiotic concentrations, soil properties and microbial diversity were assessed using a continuous random-effects model. Furthermore, the impact of biochar preparation and application conditions on the antibiotic contents in soils with different *pH* values (acidic, neutral, and alkaline), texture (coarse, medium, and fine), and SOM contents was further studied.

Results and discussion

Effect of biochar application on antibiotic contents

Applying biochar was found to effectively reduce the antibiotic content present in soil. As shown in Fig. 1, biochar significantly reduced soil SAs and TCs. Specifically, the SAs content decreased by 54.8%, while the TCs content decreased by 20.9%. This effect is primarily attributed to the adsorption mechanisms of biochar[7]. The main mechanisms include π-π bonding between the aromatic rings of biochar and antibiotic molecules[15].

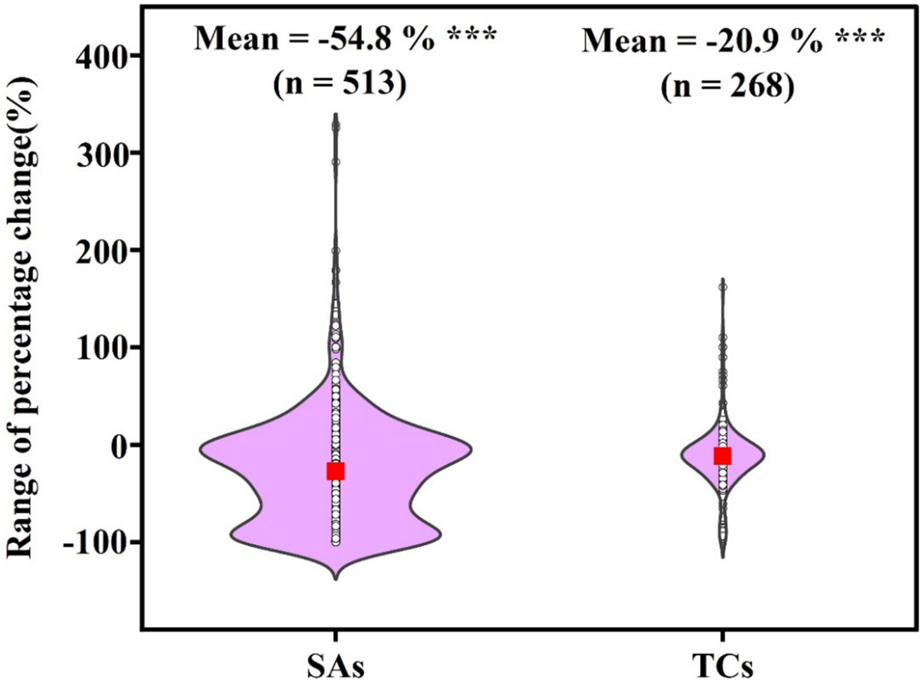

Fig. 1. Effect of biochar application on antibiotic contents. SAs = sulfonamides, TCs = tetracyclines.

For example, biochar enhances the adsorption of TCs through π-π interactions and metal bridging, thereby converting free TCs into bound forms and effectively removing them from the soil[19]. In addition, electrostatic attraction, hydrogen bonding, pore occupation, cation bridging and surface complexation all play a crucial role in the adsorption of antibiotics[20]. Furthermore, this study found that biochar was more effective in removing SAs than TCs, primarily due to differences in their physicochemical properties and adsorption mechanisms[9]. SAs are more hydrophobic and smaller in molecular size, facilitating hydrophobic interactions and micropore filling with biochar[2]. In contrast, the larger molecular structure and distinct ionization states of TCs result in size exclusion and weaker electrostatic interactions, limiting their adsorption[9]. In addition, the predominance of SAs in both concentration and frequency, combined with their low biodegradability and rapid transport, makes them highly mobile in soil[21].

Effects of biochar application on soil properties and microbial diversity

According to Figure·2a, with the addition of biochar, soil *pH* increased by 3.2% (95% CI: 1.8% to 4.6%), which was primarily due to its alkaline composition, ash-derived Ca^{2+}, K^+ and Mg^{2+} and carbonates, and biochar's capacity to decrease exchangeable acidic cations (Al^{3+} and H^+)[23]. At the same time, the increase in soil *pH* promotes an increase in DOC, as higher *pH* enhances the solubility of SOM, thereby facilitating the release of DOC[23]. As a result, DOC increased by 46.4% (95% CI: 32.1% to 60.7%) (Fig. 2a). In addition, CEC increased by 19% (95% CI: 0.2% to 37.8%) (Fig. 2a), likely due to biochar's larger surface area, increased negative surface charge, and higher charge density[24]. These properties enhance the CEC by providing more active sites for cation retention[25]. The greater surface area provides more adsorption sites, while the negative surface charge and high charge density facilitate the attraction and reversible binding of positively charged ions, including Ca^{2+}, Mg^{2+}, K^+, and NH_4^+[27]. Moreover, SOM increased by 36.5% (95% CI: 11.1% to 61.9%) (Fig. 2a), which results from the contribution of stabilized organic carbon from biochar and elevated SOM retention through adsorption mechanisms[27]. TOC also increased by 47.4% (95% CI: 36.2% to 58.6%) (Fig. 2a). This is because biochar contains mineral nutrients, which are released into the soil upon application, thereby increasing soil nutrient availability[11]. In addition, the enhancement of TOC content stems from increased carbon stability, high adsorption capability of organic compounds, and reduced utilization by microorganisms[28].

Figure 2b illustrates that soil microbial diversity increased significantly. The Chao and Shannon indices increased by 19.8% (95% CI: 15.4% to 24.2%) and 6.9% (95% CI: 1.4% to 12.4%), respectively. Microbial diversity assessment is very important for monitoring the restoration of soil ecosystems[29]. Biochar significantly increases microbial diversity and abundance in soil, suggesting its potential to ecologically remediate antibiotic-contaminated soil[30]. This may result from the favorable habitat that biochar-amended soil provides for microorganisms.

Biochar has a rich and complex pore structure that gives rise to numerous micropores[7]. These micropores create a favorable microenvironment that supports microbial growth and reproduction, shields microorganisms from adverse external conditions, and thereby reduces interspecies competition for survival[30]. In addition, the previously mentioned increases in SOM, soil TOC, and related parameters provide favorable conditions for increased microbial diversity[31]. The increase in SOM indicates a corresponding rise in soil organic carbon, a key factor influencing soil microbial biomass[32]. SOM and TOC can serve as a carbon source for soil microorganisms, providing a steady nutrient flow and expanding the microbial ecological niche[33].

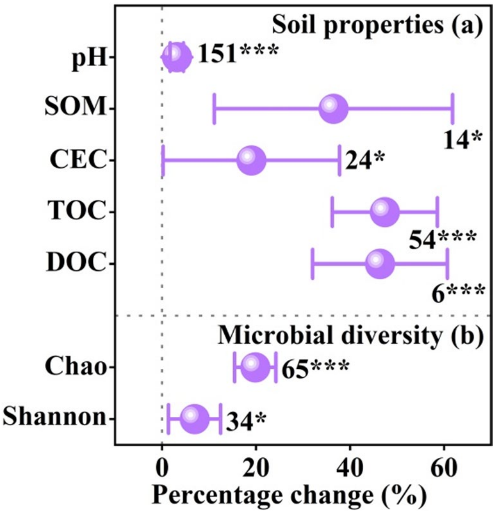

Fig. 2. Effect of biochar application on (**a**) soil properties and (**b**) Microbial diversity. Error bars represent 95% confidence intervals. A significant effect is indicated when the 95% confidence interval does not overlap zero. Sample size for each parameter are shown as numbers adjacent to the error bars. Statistical significance is denoted as follows: *, $p < 0.05$, and ***, $p < 0.001$, respectively. SOM = soil organic matter, CEC = cation exchange capacity, TOC = total organic carbon, DOC = dissolved organic carbon.

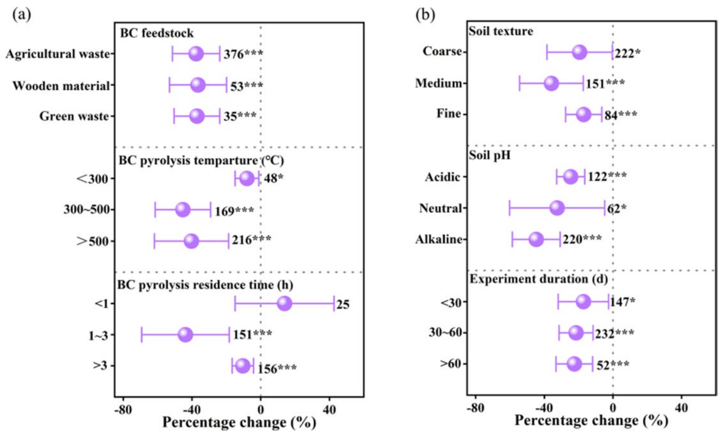

Fig. 3. Effect size of biochar application on soil SAs content. Factors analyzed include biochar feedstock type, pyrolysis temperature, pyrolysis residence time, soil texture, soil pH, and experiment duration. Error bars represent 95% confidence intervals. A significant effect is observed when the 95% confidence interval does not overlap zero. Sample sizes for each factor are indicated by the numbers adjacent to the error bars. Statistical significance is denoted as follows: *, $p < 0.05$, and ***, $p < 0.001$, respectively. BC = biochar.

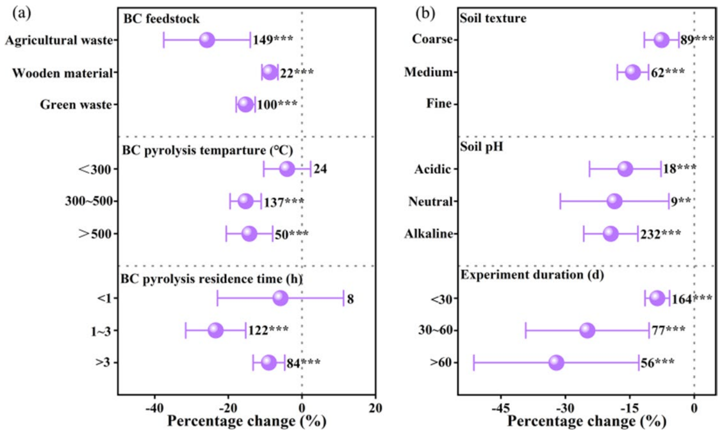

Fig. 4. Effect size of biochar application on soil TCs content. Factors analyzed include biochar feedstock type, pyrolysis temperature, pyrolysis residence time, soil texture, soil pH, and experiment duration. Error bars represent 95% confidence intervals. A significant effect is observed when the 95% confidence interval does not overlap zero. Sample sizes for each factor are indicated by the numbers adjacent to the error bars. Statistical significance is denoted as follows: **, $p < 0.005$, and ***, $p < 0.001$, respectively. BC = biochar.

Effects of biochar properties on antibiotics

Types of feedstocks used for Biochar production

According to Fig. 3a, biochar produced from agricultural and green waste achieved the greatest reduction of SAs in soil, at 37.6% (95% CI: −51.4% to −23.8%) and 37.1% (95% CI: −50.4% to −23.8%), respectively. A comparable reduction of 36.5% (95% CI: −53.1% to −19.9%) was observed for biochar from wooden material (Fig. 3a). Moreover, biochar produced from agricultural waste had the greatest reduction in the content of TCs at 25.8% (95% CI: −37.6% to −14.0%), while those derived from green waste and wooden material led to lower decreases of 15.3% (95% CI: −17.9% to −12.7%) and 8.7% (95% CI: −10.9% to −6.5%), respectively (Fig. 4a).

This meta-analysis elaborated that biochar derived from agricultural waste exhibited the highest efficiency in removing both SAs and TCs from soil. This finding is consistent with previous research. According to a study by Zhang et al.[35], peanut straw biochar exhibits significantly greater pore development and surface area relative to other biochar types, which facilitates the provision of additional adsorption sites and improves the physical adsorption of SAs and TCs. Furthermore, Haider et al.[6] reported that biochar derived from corn and wheat stover consistently achieved higher removal efficiency for TCs than biochar produced from other feedstocks. This may be attributed to the variability in the functional group composition of biochar produced from different feedstocks[18]. In particular, biochar produced from agricultural waste retains abundant oxygen-containing functional groups, such as carboxyl groups (-COOH) and hydroxyl groups (-OH), which can engage in strong hydrogen bonding interactions with the sulfonamide groups ($-SO_2NH_2$) in SAs and the hydroxyl groups in TCs[35]. In addition, agricultural waste biochar typically contains high contents of ash and alkaline metal oxides (e.g., Ca^{2+}, Mg^{2+}, K^+)[37]. These metal ions not only contribute to the increased alkalinity of biochar, but also participate in the formation of cation bridging structures with TCs or SAs molecules in soil[37]. In particular, under alkaline conditions, TCs tend to become negatively charged and are more likely to form stable complexes with Ca^{2+} ions, thereby enhancing their removal efficiency from the environment[38].

Biochar production conditions

Biochar generated under different pyrolysis temperatures exhibits varied characteristics that influence the degree and rate of antibiotic degradation[13]. Biochar produced at intermediate pyrolysis temperature (300–500 °C) significantly reduced the content of SAs by 45.3% (95% CI: −61.4% to −29.2%) compared to those generated at high pyrolysis temperatures (> 500 °C) (40.3%, 95% CI: −61.9% to −18.7%) and low pyrolysis temperatures (< 300 °C) (8%, 95% CI: −14.9% to −1.1%), respectively (Fig. 3a). Similarly, biochar produced at intermediate pyrolysis temperatures (300–500 °C) exhibited the greatest reduction in TCs content, with the highest removal of 15.3% (95% CI: −19.5% to −11.1%), compared with biochar at > 500 °C (14.3%, 95% CI: −20.6% to −8.0%) (Fig. 4a). However, biochar produced at < 300 °C had little effect on the TCs content in soil ($p = 0.22$).

In this study, both SAs and TCs are found to be the most effective when biochar is generated at moderate pyrolysis temperatures (300–500 °C). On the one hand, low-temperature pyrolysis cannot fully utilize the potential of biochar[39]. In general, incomplete carbonization at lower pyrolysis temperatures results in a lower degree of aromatization, as well as limited development of surface area and pore structure[40]. On the other hand, higher pyrolysis temperatures increased the carbon content of biochar while decreasing its hydrogen and oxygen contents, resulting in a marked decrease in the atomic H/C and O/C ratios[41]. This reflects a decline in biochar polarity, accompanied by enhanced aromaticity and carbonization[12]. Numerous studies have demonstrated that higher pyrolysis temperatures enhance the specific surface area of biochar, thereby facilitating more effective antibiotic remediation[41]. However, excessively high temperatures can reduce surface functionality. According to Chen et al.[43], when the pyrolysis temperature exceeded a critical temperature of 700 °C, the porous structure began to collapse due to over-carbonization, resulting in a slight decline in functional group abundance. Moreover, increasing pyrolysis temperature makes biochar less polar and reduces surface groups that form hydrogen bonds, weakening its ability to bond with TCs[43]. However, biochar made at moderate temperatures retains more surface groups and organic matter, which helps hydrogen bonding and CEC, making it better at adsorbing antibiotics[19]. Similarly, Nkoh et al.[45] reported that rapeseed straw and corn biochar exhibited the highest CEC at medium pyrolysis temperatures, such as 500℃.

The pyrolytic residence time of biochar significantly modulated the removal efficiency of SAs and TCs. The degradation of SAs (−43.8%; 95% CI: −69.3% to −18.3%) and TCs (−23.4%; 95% CI: −31.5% to −15.3%) was significantly enhanced by biochar produced at medium pyrolysis residence times (1–3 h). Extending the pyrolysis residence time to 3 h significantly reduced the degradation efficacy of biochar for both SAs and TCs, with reductions of 10.4% (95% CI: −16.6% to −4.2%) and 9.0% (95% CI: −9.7% to −4.3%), respectively (Figs. 3 and 4), which could be attributed to the excessive carbonization leading to pore collapse, loss of functional groups, and consequently, reduced adsorption capacity[43]. At a short pyrolysis residence time (< 1 h), biochar application had no statistically significant effect on the contents of SAs ($p = 0.45$) and TCs ($p = 0.53$) in soil. This may be attributed to the release of dissolved organic matter (DOM) from under-carbonized biochar, which forms hydrogen bonds with antibiotics and consequently inhibits the degradation of SAs and TCs[39].

Influence of soil properties on changes in antibiotic content

Biochar application reduces antibiotic contents in various types of contaminated soil. The largest reduction in SAs content was 35.9% (95% CI: −54.4% to −17.4%) in the medium-textured soil (Fig. 3b). In comparison, the content of SAs declined by 19.4% (95% CI: −38.4% to −0.4%) in coarse-textured soils and by 17.1% (95% CI: −27.6% to −6.6%) in fine-textured soils (Fig. 3b). In addition, TCs content decreased by 7.6% (95% CI: −11.6% to −3.6%) and 14.3% (95% CI: −17.9% to −10.7%) in coarse and medium-textured soils, respectively (Fig. 4b). Overall, biochar exhibited greater removal efficiency for SAs and TCs in medium-textured soils compared to coarse and fine-textured soils. This is because medium-textured soils have a balanced pore structure, moderate water retention and aeration, which together provide a conducive environment for promoting antibiotic adsorption and microbial degradation compared to coarse and fine-textured soils[45]. In contrast, coarse-textured soils drain rapidly, reducing the contact time between antibiotics and biochar, whereas fine-textured soils retain excessive water, which increases the solubility and diffusion of antibiotics in the soil solution but may limit their direct contact with biochar, thereby reducing adsorption efficiency. Similar findings had been reported previously. Yue et al.[15] found that biochar application to loamy soils significantly enhanced the removal of TCs, achieving efficiencies of up to 69%, which was substantially higher than that observed in sandy soils. This difference may result from the greater CEC and organic matter content in loamy soils, which facilitates antibiotic transformation processes[25].

Moreover, soil *pH* may play a crucial role in influencing both the efficiency and degree of antibiotic degradation. The analysis demonstrated that SAs content were reduced more significantly in alkaline soils by 44.7% (95% CI: −58.6% to −30.8%) compared to acidic (24.6%; 95% CI: −32.8% to −16.4%) and neutral (32.5%; 95% CI: −60.2% to −4.8%) soils (Fig. 3b). In addition, for TCs, the reductions in acidic, neutral, and alkaline soils were not significantly different, with decreases of 16.1% (95% CI: −24.4% to −7.8%), 18.5% (95% CI: −31.1% to −5.9%), and 19.4% (95% CI: −25.7% to −13.1%), respectively (Fig. 4b). These results can be explained as follows. Under alkaline conditions, SAs and TCs exist in a negatively charged form with increased polarity and solubility[46], which enhances their mobility in the soil solution and increase their susceptibility to microbial degradation or chemical breakdown[47]. In addition, high *pH* can promote hydrolysis and other degradation reactions, and alter the adsorption interface of biochar by enhancing surface charge and functional group activity, thereby further facilitating antibiotic removal[46]. Mei et al.[49] found that under alkaline conditions,

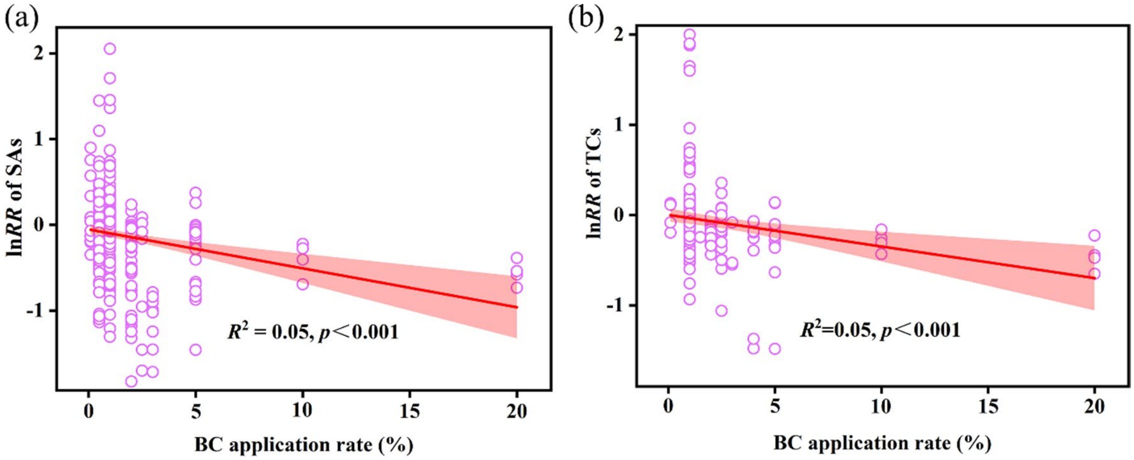

Fig. 5. Linear relationships between lnRR of SAs (**a**) and lnRR of TCs (**b**) and the response ratio of biochar application rate. The red shading indicates the 95% confidence interval of the regression slope.

biochar exhibited a significant increase in oxidized functional groups, specific surface area, and pore volume, which collectively contributed to improved antibiotic adsorption. Furthermore, microbial diversity is typically enhanced under alkaline conditions, thereby facilitating biodegradation processes[49]. For instance, *Actinobacteria* exhibited optimal tetracycline degradation at alkaline *pH*[51].

Effect of experimental time and Biochar application rate on antibiotic content

When the experimental duration was within 30 days, biochar reduced the contents of SAs and TCs in soil, with reductions of 17.2% (95% CI: −31.9% to −2.5%) and 8.6% (95% CI: −11.5% to −5.7%), respectively (Figs. 3b and 4b). When the experimental duration was 30–60 days, the SAs and TCs content decreased 21.5% (95% CI: −31.4% to −11.6%) and 24.9% (95% CI: −39.3% to −10.5%), respectively (Figs. 3b and 4b). When the experimental duration exceeded 60 days, the contents of SAs and TCs exhibited the most significant reductions, with decreases of 22.5% (95% CI: −33.2% to −11.8%) and 32.1% (95% CI: −51.3% to −12.9%), respectively (Figs. 3b and 4b). The removal efficiency of biochar for SAs and TCs gradually increases with prolonged experimental duration, indicating that long-term application is required to achieve optimal removal performance[9]. Short exposure times may limit the full activation of the functional properties of biochar. Over time, biochar undergoes surface oxidation in soil, forming more oxygen-containing functional groups (e.g., -COOH, -OH), which enhances hydrogen bonding and complexation with antibiotics, thereby enhances adsorption capacity[51]. Additionally, its porous network also provides microhabitats for microbial attachment and biofilm formation, enabling the continuous secretion of degradative enzymes and sustained biodegradation during long-term experiments[52]. Moreover, prolonged exposure allows soil microorganisms to gradually adapt to the environment, thereby further enhancing removal efficiency[53].

Additionally, the contents of SAs ($R^2 = 0.05$, $p < 0.001$) and TCs ($R^2 = 0.05$, $p < 0.001$) in soil decreased as the biochar application increased (Fig. 5). This is because increasing biochar application provides more pores and a larger surface area, which in turn facilitates greater antibiotic adsorption[54]. According to Shi et al.[57], higher application rates led to a significant increase in the adsorption capacity of peanut straw biochar toward SAs. Similarly, Li et al.[56] found that the abundant micropores in peanut shell biochar provided effective physical sorption sites for tetracycline molecules via pore-filling and van der Waals interactions, and higher application rates significantly enhanced total surface area and adsorption capacity. Moreover, the provision of more biochar offered an additional microbial habitat and increased microbial activity, which accelerated the breakdown of SAs and TCs[18]. Additionally, biochar contained mineral components that complexed with or catalyzed the degradation of antibiotics, and higher application rates provided more of these minerals, which enhanced antibiotic fixation and decomposition[56].

Limitations

This research finding has important implications for developing effective remediation approaches for soils affected by SAs and TCs. However, this study has limitations. Firstly, although this study analyzed the effects of biochar on SAs and TCs in soil, it did not investigate other types of antibiotics. This is because the data on other types of antibiotics were limited and insufficient for analysis. Therefore, future studies should further analyze this.

Moreover, this study did not examine the effect of pyrolysis rate on the antibiotic removal efficiency of biochar in soil. The pyrolysis rate is a critical parameter during biochar production, as it not only influences production efficiency but also alters the properties of the resulting biochar[18]. A rapid pyrolysis rate may damage the internal cellular structure of the biomass, leading to a reduction in porosity and specific surface area, which play a crucial role in regulating the adsorption capacity of biochar[57]. Therefore, future research should systematically evaluate how variations in pyrolysis rate affect the structural integrity and functional performance of biochar in contaminant removal.

Finally, due to data constraints, this study was unable to assess the influence of experimental type on the research results (experimental type refers to field experiments, laboratory experiments or greenhouse experiments). Among the studies we statistically analyzed, only two were field experiments. This was unexpected. This striking imbalance highlights a critical gap in current research. While laboratory and greenhouse experiments offer controlled environments that facilitate mechanistic understanding, they may not fully capture the complex interactions and variability present in real-world settings. In contrast, field experiments provide more representative and ecologically valid results, accounting for factors such as weather, microbial diversity, and native soil properties[29]. Therefore, future research should further conduct field experiments to verify the analysis results.

Conclusions

This meta-analysis revealed biochar led to significant reductions in the concentrations of SAs and TCs in soil by 54.8% and 20.9%, respectively. To investigate the effectiveness of biochar in removing antibiotics from soil, this study systematically analyzed the influencing factors in the removal of antibiotics by biochar, including biochar application conditions, soil properties, and experimental duration. Further, biochar-mediated changes in antibiotic contents enhanced soil microbial diversity. These findings provided valuable insights into the potential of biochar for remediating soils contaminated with SAs and TCs. The mechanism of accelerated antibiotic removal by biochar may be related to biochar characteristics, soil properties, and the indirect effect of biochar in altering soil properties. Accordingly, choosing an appropriate type of biochar to enhance antibiotic removal can support the development of an economically viable strategy for soil remediation. Future studies could explore the effects of biochar on other antibiotic classes and assess its long-term field applications and environmental impacts. Such research would enhance the understanding of the potential of biochar in soil remediation and inform sustainable and cost-effective strategies to mitigate antibiotic contamination.

Data availability

Data will be made available on request.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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