MODELLING THE EFFECTS OF BIOCHAR ON SOIL CHEMICAL AND MICROBIOLOGICAL PROPERTIES USING META-REGRESSION

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Abstract. The effects of biochar on soil fertility, carbon storage, and microbiological processes vary considerably depending on feedstock, pyrolysis conditions, application rate, and the initial properties of the soil. The purpose of this work is to systematize the quantitative evidence published in the literature on the effects of biochar and to establish a scientific and methodological foundation for building a meta-regression model that will subsequently incorporate individual study-level data. The primary sources underlying this work are a global meta-analysis covering 59 studies, a global meta-analysis of soil chemical properties, a microbiological meta-analysis covering 49 studies and 265 datasets, and a 2025 biochar–microorganism meta-analysis drawing on 56 studies and 356 individual data points. According to the published results, biochar application increased soil pH, cation exchange capacity, and organic carbon by 46%, 20%, and 27%, respectively, decreased bulk density by 29%, and increased porosity by 59%. For chemical indicators, Hedges' d was 0.50 for SOC, 0.44 for the C:N ratio, 0.39 for pH, 0.35 for total carbon, 0.21 for EC, and 0.20 for CEC. The microbiological effects of biochar can likewise be positive, although they depend on biochar properties and soil conditions. The 2025 meta-analysis showed that combining biochar with a microbial inoculant can increase soil nitrogen, SOC, and crop productivity relative to biochar applied alone. This article does not fabricate new experimental results; final meta-regression coefficients should only be calculated once individual study-level data have been fully digitized. This approach preserves scientific integrity while enabling the development of a predictive model for designing future field experiments and climate-adapted soil management systems.

Keywords. biochar; meta-regression; soil fertility; soil organic carbon; pH; CEC; microbiological activity; microbial inoculant; pyrolysis temperature; climate-adapted soil.

Introduction. Agricultural soil degradation, loss of organic carbon, and climate change are closely interlinked processes. Carbon storage in soil is important not only for productivity but also for managing greenhouse gas balances and improving water-use efficiency. From this standpoint, biochar produced through biomass pyrolysis is regarded, alongside organic and mineral resources, as one of the most promising tools for soil management.

The effect of biochar on soil depends on its porosity, surface area, pH, ash content, functional groups, and stable carbon fraction. An increase in pyrolysis temperature generally increases the aromaticity and structural stability of biochar, but nutrient availability and microbiological response may also change. Consequently, a universal conclusion such as "the more biochar, the better" is not scientifically valid.

The global meta-analysis by Singh and co-authors drew on data from 59 studies published between 2012 and 2021. The authors showed that biochar application increased soil pH, CEC, and organic carbon by 46%, 20%, and 27%, respectively, decreased bulk density by 29%, and increased porosity by 59%. Biochar doses ranged from 5 to 150 t/ha. Biochar produced at higher pyrolysis temperatures (>500 °C) produced a stronger response in bulk density and porosity, whereas low-temperature biochar had a stronger effect on certain microbial diversity indicators.

The global meta-analysis by Sun and co-authors expressed the effects of biochar on chemical indicators using Hedges' d. The highest value was 0.50 for SOC, 0.44 for the C:N ratio, 0.39 for pH, 0.35 for TC, 0.21 for EC, and 0.20 for CEC. In an aggregated boosted-tree analysis, biochar application rate, initial soil pH, and sand content were identified as the primary explanatory factors.

The microbiological component is one of the central elements of the biochar–soil system. The meta-analysis by Zhang and co-authors, summarizing 265 datasets across 49 studies, showed that microbial biomass and activity may increase following biochar application. At the same time, the response depended on the nutrient composition, surface area, porosity, soil pH, and nutrient status of the biochar.

Combining biochar with microorganisms is an important direction for the next stage of research. The 2025 meta-analysis by Ross and Emery, covering 56 studies, showed that adding a microbial inoculant together with biochar can increase soil N, SOC, and yield relative to biochar alone. The authors noted that the effect depended on the source of the inoculant, the type of inoculant, and the experimental conditions. The availability of 356 individual data points in this article is of particular importance.

This evidence indicates that the effect of biochar should be assessed not through a single factor but through a model that jointly accounts for biochar dose, pyrolysis temperature, initial soil condition, experiment duration, and the microbiological component. Meta-regression makes it possible to bring such heterogeneous experiments into a common statistical framework.

Aim and Objectives of the Study. The aim of the study is to assess the effect of biochar on soil chemical and microbiological properties on the basis of published quantitative data, and to develop a meta-regression model that accounts for biochar dose and soil–biochar conditions.

- systematize the quantitative meta-analyses on biochar;
- identify the variables from individual studies to be included in the model;
- assess the effect of biochar dose, pyrolysis temperature, and initial soil pH on response indicators;
- consider the combined effect of biochar and microbial inoculant as a separate moderator;

- assess the model's heterogeneity, confidence intervals, and statistical significance;
- identify predictions and optimal ranges for future field experiments.

Materials and Methods.

Source selection strategy. The core evidence was drawn from meta-analyses published in peer-reviewed international journals. Singh et al. (2022), Sun et al. (2022), Zhang et al. (2018), and Ross & Emery (2025) were selected as the primary sources. These studies quantitatively assess, respectively, the physicochemical and microbiological properties of biochar, soil chemistry, microbial biomass/activity, and the combination of biochar with microbial inoculants. Singh et al. draws on 59 studies and the pairwise data in Supplementary Table S1; Ross & Emery provides a separate XLSX file covering 56 studies and 356 individual data points.

Data extraction.

Variable	Symbol	Unit/Code	Role
Biochar application rate	X1	t ha−1	independent
Pyrolysis temperature	X2	°C	independent
Initial soil pH	X3	pH	independent
Experiment duration	X4	days	independent
Microbial inoculant	X5	0/1	moderator
Soil texture	X6	sand/silt/clay or categorical	moderator
SOC	Y1	g kg−1 or %	response
pH	Y2	pH	response
CEC	Y3	cmolc kg−1	response
Bulk density	Y4	g cm−3	response
Porosity	Y5	%	response
Microbiological indicator	Y6	unit as reported in the source article	response
Yield	Y7	t ha−1 or relative value	response

Effect size. Where treatment and control means, standard deviations, and sample sizes are available for individual studies, a standardized mean difference (Hedges' g) is calculated. Where a single indicator is reported in identical units, the log response ratio (LRR) may also be applied: LRR = ln(Xt/Xc). For articles in which the meta-analysis already reports Hedges' d, the authors' own effect-size values are retained separately and are not mixed with raw percentage changes.

Meta-regression model

The base random-effects meta-regression is expressed as follows:

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \beta_3 X_{3i} + \beta_4 X_{4i} + \beta_5 X_{5i} + u_{study} + \varepsilon_i$$

where Yi is the effect size or standardized response, Xi are the moderators, ustudy is the study-level random effect, and εi is the residual error. To examine a possible nonlinear relationship between biochar dose and temperature, a quadratic term and an interaction term are added:

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \beta_3 X_{1i}^2 + \beta_4 X_{1i} X_{2i} + \ldots + ustudy + \varepsilon_i$$

Statistical criteria

The model is evaluated using R^2 or pseudo-R^2, RMSE/MAE, the 95% confidence interval, and the p-value. Heterogeneity in the meta-regression can be examined using the Q and I^2 statistics, and publication bias using methods such as the funnel plot and Egger's test. Multicollinearity in the multi-moderator model is checked using VIF. Sensitivity analysis is carried out by sequentially removing individual studies and examining high-leverage observations.

Reproducibility

The final analysis must be preserved as a reproducible script in an R or Python environment. The data-extraction table must record, for each value, the article's DOI, the table/figure number, the treatment, the control, n, the mean, and the SD. Data digitized from a graph are flagged separately. This approach allows every figure to be traced back to its original source for verification.

Results: Quantitative Synthesis of the Published Evidence

The results below are not new experimental findings; rather, they are the summary indicators published by the authors of the selected peer-reviewed meta-analyses. They should not be interpreted as new meta-regression coefficients.

Source	Coverage	Key finding	Relevance for the model
Singh et al., 2022	59 studies	pH +46%; CEC +20%; OC +27%; bulk density −29%; porosity +59%	Dose, temperature, and texture moderators
Sun et al., 2022	global meta-analysis	Hedges' d: SOC 0.50; C:N 0.44; pH 0.39; TC 0.35; EC 0.21; CEC 0.20	Chemical responses
Zhang et al., 2018	49 studies; 265 datasets	Microbial biomass/activity may increase	Microbiological response
Ross & Emery, 2025	56 studies; 356 data points	Inoculant + biochar: positive response in N, SOC, and yield	Biochar × inoculant interaction

Biochar dose

In the Singh et al. meta-analysis, biochar application rates ranged from 5 to 150 t ha−1. The overall increase in soil organic carbon was stronger in the higher application-rate groups; the authors also showed that the response varied across different textures. This finding supports testing both linear and quadratic terms for dose in the model. However, it is not valid to treat every dose within the 5–150 t ha−1 range as "optimal" for a single agroecological setting.

Soil chemistry

Among the Hedges' d values reported by Sun et al., SOC had the largest overall effect size. Initial pH and sand content were noted as important moderators explaining the effect of biochar. This finding indicates that the effect of biochar is not independent of the soil. It is therefore advisable to include initial pH and texture as mandatory moderators in the forthcoming model.

Physical properties

In the Singh et al. meta-analysis, biochar decreased bulk density by an average of 29% and increased porosity by 59%. Biochars produced above 500 °C had a stronger effect on bulk density and porosity. This shows that the structural properties of biochar can alter the physical environment of the soil.

Microbiological response

Based on 265 datasets, Zhang et al. showed that biochar application may increase microbiological biomass and activity. However, the result depended on properties of the biochar such as nutrient content, pH, surface area, and porosity. This heterogeneity indicates the need to include moderators in the meta-regression.

Biochar and microbial inoculant

In the 2025 meta-analysis by Ross and Emery, the combination of biochar with a microbial inoculum increased soil N, SOC, and crop productivity relative to biochar alone. Fungal inocula had a stronger effect than bacterial inocula. The effect was stronger under greenhouse conditions, whereas under field conditions it was mainly limited to crop productivity. This finding indicates that experiment type should also be included in the model as a moderator.

Discussion. The available meta-analyses support a positive effect of biochar on the soil's chemical and physical status, although the responses are not uniform. The main reason for this is variation in biochar feedstock, pyrolysis temperature, dose, and soil conditions. For this reason, generalizing statements such as "biochar always increases yield" should be avoided in a manuscript intended for a reputable journal.

A Hedges' d of 0.50 for SOC indicates a substantial effect of biochar on carbon-related indicators. However, an increase in soil SOC does not automatically imply long-term carbon sequestration. The decomposition kinetics of biochar, its mineral associations, and soil–climate conditions require long-term assessment.

Microbiological responses may be related to the porous structure and surface chemistry of biochar. Pores can provide physical refuge for microorganisms, while adsorption can alter the availability of substrates and toxic compounds. At the same time, a very high biochar dose may raise pH or salinity, potentially creating unfavorable conditions for certain microorganisms.

The combination of biochar and microorganisms is one of the most promising directions for this line of research. The 2025 meta-analysis shows that positive responses depend on the source of the inoculant and the type of experiment. This means that, for application under local conditions, it is not "biochar plus any microorganism" that should be used, but rather a combination of biochar properties, microorganism type, and soil conditions selected jointly.

Beyond predicting an optimal point, the practical value of the mathematical model lies in showing which factor contributes most to the outcome. For example, if biochar dose proves to be a strong moderator, future experiments should span a wider dose gradient; if initial pH proves to be a strong moderator, it would be advisable to block experiments by pH.

The main limitation of this article is that new meta-regression coefficients cannot be published without individual data being fully pooled. The values cited above — 0.50, 0.44, 0.39 — are therefore retained as the results of the original articles. New R^2, β, and p values should only be calculated once the individual study-level dataset has been fully verified.

Practical Model and Future Experimental Design

A response-surface approach may be applied for future experiments. Biochar dose and microbial inoculant concentration are treated as the primary factors, while soil moisture and temperature are treated as controlled conditions. SOC, pH, CEC, microbial biomass C, or CO_2 flux may be selected as the response variable. The minimum sample size should be determined by power analysis before the experiment begins.

Stage	Task	Output
1	Retrieve raw supplementary files from the 56/59 source studies	Raw dataset
2	Verify treatment–control values	Cleaned dataset
3	Standardize means, SDs, n, and units	Analytical dataset
4	Compute Hedges' g or LRR	Effect-size dataset
5	Run the random-effects meta-regression	β, 95% CI, p
6	Moderator and sensitivity analysis	Robustness assessment
7	Bubble/forest/funnel plots	Visual results
8	Validation against local field trials	Model validation

Scientific Novelty

The proposed scientific novelty of this work lies in assessing biochar's chemical and microbiological soil responses within a single statistical framework that treats biochar dose, pyrolysis temperature, initial pH, soil texture, and microbial inoculant as moderators.

In particular, including the biochar + inoculant combination as a separate moderator makes it possible to regard biochar not merely as a physicochemical soil amendment but as a microbiological carrier.

Conclusion. The published meta-analyses confirm that biochar can have a significant effect on soil pH, CEC, organic carbon, bulk density, porosity, and microbiological indicators. Based on 59 studies, Singh et al. reported increases of 46%, 20%, and 27% in pH, CEC, and OC, respectively, a 29% decrease in bulk density, and a 59% increase in porosity. In the global meta-analysis by Sun et al., SOC had the highest effect size, with a Hedges' d of 0.50. Based on 265 datasets, Zhang et al. showed that microbiological biomass and activity may increase. The 2025 meta-analysis by Ross and Emery showed additional positive effects from combining biochar with microbial inoculants.

On the basis of this evidence, modelling the effect of biochar through meta-regression is scientifically justified. However, in the final article to be submitted to a reputable journal, new statistical results should only be calculated from individual study-level data. This manuscript therefore provides the verified literature results and the methodological framework for the full meta-regression; the final version must include all individual values drawn from the original supplementary datasets, the new β coefficients, 95% CIs, p-values, heterogeneity statistics, and figures.

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