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EFFECTS OF USING COAL AS AMENDMENT ON SOIL MICROBIAL COMMUNITY AND ACTIVITY

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ABSTRACT: *The use of biochar as a soil amendment to enhance soil fertility and agricultural productivity is being explored. This study investigates the impact of using coal as biochar on the availability and dynamics of organic elements, as well as its effect on soil microbial activity. The experiment was conducted on ferralsols in Mahitsy, Antananarivo, Madagascar, during the 2024 bean-growing season. Coal was applied at rates of 25, 50, 75, 100, or 125 g per planting hole, along with organic fertilizers: bat guano (30 g) or manure (150 g). Samples were collected at the pod ripening stage (R8). The results showed that applying 50 g of coal per hole significantly increased the microbial population to 1.85×10^5 colony-forming units (CFU)/g and boosted microbial activity to 3.1 µg fluorescein-H/g soil. These results suggest that using coal as biochar positively influences soil microbial dynamics and could enhance soil health and agricultural productivity.*

KEYWORDS: Coal, ferralsols, soil microbial flora, biological activity, Madagascar.

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INTRODUCTION

Soil microbial communities play a crucial role in soil function and agricultural sustainability. They regulate the decomposition of organic matter, nutrient cycling, and overall soil biological activity. Changes in microbial abundance and metabolic activity directly impact soil fertility and productivity, making microbial indicators vital for evaluating soil quality (Schloter et al., 2003; Bardgett & van der Putten, 2014).

The decline of soil organic matter and the reduction of biologically active carbon pools are major drivers of soil degradation worldwide. Therefore, carbon-based soil amendments have been widely investigated as strategies to stimulate microbial activity and restore soil biological functioning. Among these, biochar has received considerable attention due to its ability to improve soil structure, increase carbon stability, and enhance microbial activity (Lehmann et al., 2011).

Biochar increases microbial abundance and enzymatic activity by providing carbon substrates, improving aeration, and creating microhabitats favorable to microbial growth (Liang et al., 2010). However, the magnitude and direction of biochar's effects are highly variable and depend on the type of feedstock, the production conditions, and the application rate (Deenik et al., 2010). Furthermore, biochar production is limited or economically inaccessible in many regions, underscoring the necessity of exploring alternative carbon-rich materials.

Coal is a naturally occurring, carbon-rich material with structural properties comparable to biochar. Despite its widespread availability, coal has received little attention as a soil amendment. Previous studies suggest that coal-derived organic fractions may influence microbial processes and nutrient dynamics, indicating its potential relevance to soil biology (Piccolo, 2002).

This study investigates whether coal can stimulate soil microbial abundance and activity in a manner comparable to that of other carbon-rich amendments. We assessed microbial response through (i) total cultivable soil flora, which represents microbial abundance, and (ii) fluorescein diacetate (FDA) hydrolysis, which we used as an integrative indicator of overall microbial enzymatic activity. We hypothesize that coal amendments increase cultivable microbial populations and enhance microbial metabolic activity.

LITERATURE REVIEW

Cultivable Microbial Flora as an Indicator of Soil Biological Response

Although molecular techniques provide insights into microbial diversity, cultivable microbial counts remain a robust and widely used indicator of microbial abundance and responsiveness to functional changes in the soil. Cultivable flora reflects the fraction of the microbial community that is actively involved in nutrient cycling and organic matter decomposition under specific environmental conditions (Paul, 2015).

Carbon amendments often stimulate cultivable microbial populations by alleviating carbon limitation and improving soil microhabitat conditions. Increases in cultivable bacteria and fungi have been reported following the application of carbon-rich substrates, indicating enhanced microbial growth and activity (Wardle et al., 2004).

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FDA Hydrolysis as a Proxy for Global Microbial Activity

Fluorescein diacetate (FDA) hydrolysis is a well-established method for evaluating total microbial activity in soil. A broad range of microbial enzymes, including esterases, lipases, and proteases, hydrolyze FDA, providing an integrative measure of overall microbial metabolic potential (Adam & Duncan, 2001).

Since FDA hydrolysis reflects the activity of living and metabolically active microorganisms, the method is well-suited for evaluating the short- to medium-term effects of soil amendments on microbial functioning. Numerous studies have demonstrated its sensitivity to changes in carbon availability, soil management practices, and organic amendments (Green et al., 2006).

Carbon-Rich Amendments and Microbial Activity

Carbon availability is a primary limiting factor for soil microbial growth and enzymatic activity. Adding carbonaceous materials can stimulate microbial metabolism by providing energy sources and altering soil properties, such as porosity and moisture retention (Liu et al., 2016).

Studies on biochar consistently report increases in FDA hydrolysis and cultivable microbial counts, particularly in soils with low organic matter content (Lehmann et al., 2011). However, highly recalcitrant carbon forms may induce delayed or moderate microbial responses depending on their accessibility to microorganisms (Kuzyakov & Xu, 2013).

Theoretical Basis for Coal–Microbe Interactions

Like biochar, coal consists largely of aromatic carbon structures that influence soil microbial processes through physical and chemical interactions rather than rapid carbon mineralization. Coal particles can provide protective microhabitats, increase surfaces for microbial colonization, and stabilize organic compounds in soil.

Although coal is not expected to act as a readily available carbon source, it may indirectly stimulate microbial activity by interacting with soil organic matter and improving habitat conditions and nutrient retention. This conceptual framework supports the hypothesis that adding coal to soil can increase cultivable microbial populations and global enzymatic activity, even without highly labile carbon inputs.

METHODOLOGY

An experimental field study was conducted in November 2024 in a village located in the rural town of Mahitsy, Antananarivo, Madagascar. The village's coordinates are S18°46'15.96", E47°20'59.68". The study site is in a tropical, hot, and humid climate. From November 2024 to March 2025, the average monthly precipitation was 117 mm, and the average temperature was 22.3°C. These climatic conditions, particularly the low precipitation levels, were not ideal for cultivation and required close monitoring of soil water reserves.

The soil type in the study area is classified as ferralsol grassland, which is characterized by its acidic nature and yellow-red to red coloration.

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The biochar material used in this experiment was coal derived from the Sakoa deposit in southwestern Madagascar. The coal underwent coking, grinding, and sieving to a particle size of 2 mm prior to application. The initial physicochemical properties (Table 1) include:

Density: 1.8 g/cm³, Sulfur content: 0.6%; Calorific value: 6,500 kcal/kg.

Table 1: Physicochemical analysis of initials soil-amendments parameters (coal, charcoal, guano, manure)

Elements	pH	N (%)	P assim (ppm)	Ca (%)	Mg (%)	K (%)	Na (%)	CEC (cmol /kg)	CO (%)	MO (%)
coal	8,13	0,98	12,20	0,52	0,06	0,02	0,08	5,27	9,35	16,082
charcoal	7,55	0,58	3,89	0,09	0,04	0,16	0,1	34,8	4,38	7,5336
Guano	6,20	5,06	12,60	21,30	1,94	2,01			13,20	22,7
Manure	8,05	2,17	1,17	1,90	0,61	1,75	0,80		20,9	35,9
Mahitsy soil (0-15 cm)	5,14	0,10	3,70	2,55	1,58	0,51	0,35	7,3	1,00	1,72

Two organic amendments commonly used in Madagascar—livestock manure and bat guano—were selected as baseline nutrient sources. Manure was applied at 150 g per planting hole and guano at 30 g per planting hole, reflecting prevailing farmer practices. Each planting hole contained three plants.

The experiment followed a randomized complete block design with two amendment-based blocks (manure and guano). Within each block, six coal application rates (0, 25, 50, 75, 100, and 125 g per planting hole) were randomly assigned and replicated three times. The organic amendment was applied uniformly within each block and served as a standard base input, while coal constituted the sole experimental factor. The 0 g coal treatment served as the control and received the respective baseline amendment.

Coal rates were selected to span a practical and agronomically realistic range, from a minimum feasible dose (25 g) to a high application rate (125 g), enabling robust evaluation of dose–response relationships and identification of potential thresholds or optima. Incremental increases of 25 g were chosen to ensure sufficient resolution for modeling response curves while maintaining field applicability.

Each plot measured 4 m × 2 m, with planting holes spaced at 20 cm × 40 cm, corresponding to a plant density of approximately 100,000 plants ha^{-1} (Table 2). Each block comprised 18 plots (6 treatments × 3 replicates), resulting in 36 plots in total.

Table 2: Treatment name

Quantity of fertilizer	Quantity of coal (g)	Treatments name
150 grams of manure per bunch	0	T0
	25	T1
	50	T2
	75	T3

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	100	T4
	125	T5
30 grams of guano by bunch	0	TA
	25	TB
	50	TC
	75	TD
	100	TE
	125	TF

Soil samples were collected on February 11, 2025, at the end of the pod maturation stage.

Enumeration of total cultivable soil flora

Total cultivable soil flora refers to the fraction of microorganisms capable of proliferating on nutrient-rich media under controlled laboratory conditions. To enumerate these microorganisms, Tryptic Soy Agar (TSA) medium supplemented with 2% agar was used.

Soil samples (10 g fresh weight) were suspended in 90 mL of sterile physiological saline solution (0.85% NaCl) and homogenized by shaking for 30 min to obtain a 10^{-1} dilution. Serial 10-fold dilutions were subsequently prepared up to 10^{-6}. From appropriate dilutions (10^{-3} to 10^{-6}), 100 µL aliquots were aseptically spread onto TSA plates in triplicate.

Plates were incubated at 30 °C under dark conditions, and colony-forming units (CFUs) were counted after 24, 48, and 72 h. Only plates containing 30–300 colonies were considered for enumeration to ensure statistical reliability.

Microbial abundance was expressed as CFU per gram of dry soil and calculated as:

$$\text{CFU g}^{-1} = \frac{N \times D}{V \times W}$$

where N is the number of colonies counted, D is the dilution factor, V is the plated volume (mL), and W is the dry weight equivalent of soil (g). All counts were performed in triplicate, and mean values were used for statistical analysis.

This approach provides a quantitative estimate of viable heterotrophic microbial populations and allows assessment of treatment effects on soil microbial activity.

Measurement of total soil microbial activity

Soil microbial activity was quantified using fluorescein diacetate (FDA) hydrolysis, a widely used method for assessing total microbial enzymatic activity. This approach measures the enzymatic conversion of FDA into fluorescein, following the protocol described by Schnürer and Rosswall (1982). A 1 g soil sample, previously sieved through a 2 mm mesh to remove debris and ensure homogeneity, was suspended in 15 mL of phosphate buffer (pH 7.6). To initiate the enzymatic reaction, 200 µL of FDA solution (1 mg/mL) was added to the mixture. The samples were incubated at 30°C for 1 hour under continuous shaking to maintain uniform reaction conditions and facilitate substrate diffusion.

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Following incubation, the reaction was terminated by adding 15 mL of analytical-grade acetone to each sample (soil suspension volume: 5 mL), resulting in a final acetone concentration of 75% (v/v), which precipitated any unhydrolyzed fluorescein diacetate (FDA). The samples were then centrifuged at 10,000 rpm for 5 minutes to separate the supernatant containing fluorescein. The optical density (OD) of the supernatant was measured at 490 nm using a spectrophotometer, as described by Alef (1998). Fluorescein concentrations were determined by referencing a standard calibration curve, and microbial enzymatic activity was expressed as the amount of fluorescein released per hour per gram of soil (μg fluorescein•h^{-1}•g^{-1}). This method provides a reliable and quantifiable assessment of microbial activity, allowing for a comparative evaluation of enzymatic functions across different soil treatments. Understanding microbial activity is essential for elucidating the role of soil amendments in promoting microbial metabolism and overall soil health.

Statistical data analysis

The data were analyzed using one way analysis of variance (ANOVA) to assess significant differences among treatments. Post hoc comparisons were conducted using the Newman-Keuls test at a significance level of $P < 0.05$. All statistical analyses were performed using STATISTICA software to ensure rigorous evaluation of treatment effects.

RESULTS

Effects of coal application on microbial flora (Table 3, Table 4)

The results demonstrate that the addition of coal significantly enhanced the cultivable microbial population compared to the control treatments. This increase was most pronounced at an application rate of 50 g per pocket in treatments with either guano or manure (T2 and TC, respectively; $p < 0.05$). However, when coal application rates exceeded 75 g per pocket, a decline in the total microbial flora was observed, irrespective of the type of fertilization.

Table 3: Average of total flora and the quantity with manure experiment

Treatments	Total flora UFC/g ±SD
T0	$3{,}30.10^4 \pm 473{,}57^e$
T1	$6{,}48.10^4 \pm 311{,}65^c$
T2	$1{,}85.10^5 \pm 1851{,}07^a$
T3	$8{,}82.10^4 \pm 226{,}31^b$
T4	$5{,}31.10^4 \pm 218{,}61^d$
T5	$4{,}71.10^4 \pm 297{,}58^d$
F (p)	60700 p<0,05

Numbers followed by the same letter within a column are not significantly different at the level of probability 0,05 based on Newman Keuls test

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Table 4: Average of total flora and the quantity with guano experiment

Treatments	Total flora UFC/g
TA	$4{,}32.10^4 \pm 192{,}62^c$
TB	$7{,}03.10^4 \pm 46{,}56^a$
TC	$7{,}12.10^4 \pm 292{,}52^a$
TD	$5{,}46.10^4 \pm 101{,}00^b$
TE	$4{,}68.10^4 \pm 313{,}33^c$
TF	$4{,}38.10^4 \pm 399{,}93^c$
F (p)	88200 $p < 0.05$

Numbers followed by the same letter within a column are not significantly different at the level of probability 0,05 based on Newman Keuls test

Effect of coal application on total microbial activity (Table 5, Table 6, Fig 1)

Enzymatic activity, assessed through the hydrolysis rate of fluorescein diacetate, was significantly influenced ($p < 0.05$) by the addition of coal to the soil used for bean cultivation. Biochar applications of 25 g or 50 g per pocket (T1, T2, TB, TC) resulted in more than a twofold increase in enzymatic activity compared to the control (T0 = 1.4; $p < 0.05$).

Table 5: Average of fluorescein activity with manure experiment

Treatments	FDA (µg de fluorescéine.h^{-1}.g^{-1} de sol)
T0	$1{,}4 \pm 0{,}20^e$
T1	$2{,}4 \pm 0{,}09^b$
T2	$3{,}7 \pm 0{,}1^a$
T3	$2{,}6 \pm 0{,}1^b$
T4	$2{,}0 \pm 0{,}11^c$
T5	$1{,}9 \pm 0{,}13^d$
F (p)	105,7 p<0,05

Numbers followed by the same letter within a column are not significantly different at the level of probability 0,05 based on Newman Keuls test

Table 6: Average of fluorescein activity with guano experiment

Treatments	FDA (µg de fluorescéine.h^{-1}.g^{-1} de sol)
TA	$1{,}9 \pm 0{,}08^c$
TB	$2{,}4 \pm 0{,}07^a$
TC	$2{,}5 \pm 0{,}13^a$
TD	$2{,}1 \pm 0{,}10^b$
TE	$1{,}9 \pm 0{,}09^c$
TF	$1{,}9 \pm 0{,}10^c$
F (p)	80,5 p <0,05

Numbers followed by the same letter within a column are not significantly different at the level of probability 0,05 based on Newman Keuls test

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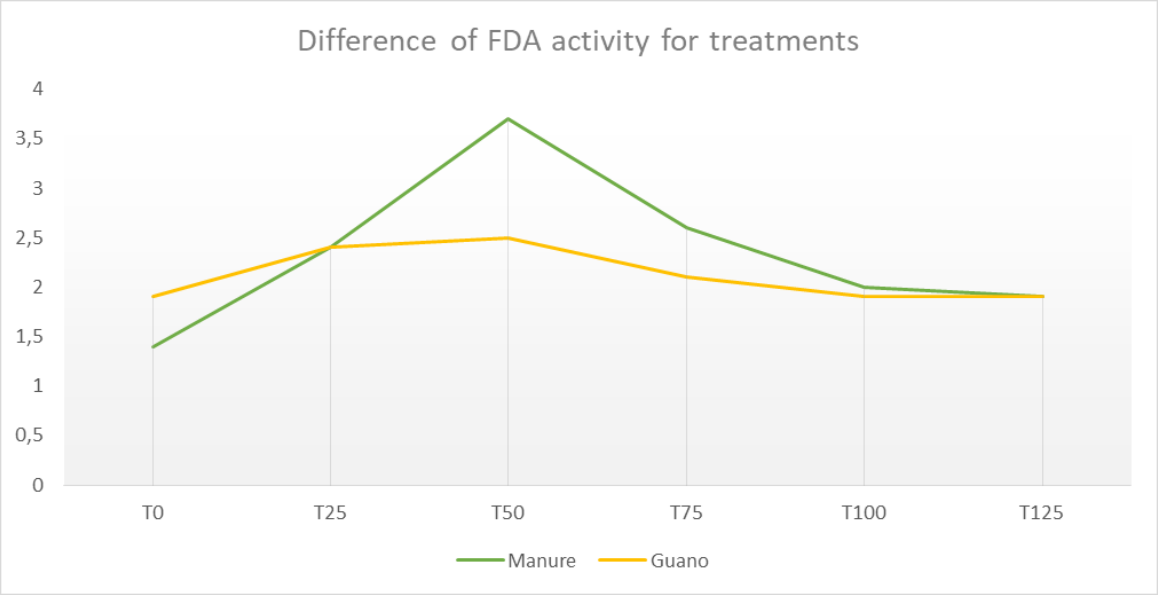
As the hydrolysis reaction product reflects total microbial activity in the soil, the application of 50 g of biochar notably stimulated microbial activity. However, the results do not provide insights into which specific microbial groups or taxa were primarily affected by this enhancement.

Figure 1: FDA activity for treatments



DISCUSSIONS

Improvement of Total Flora by Adding Coal

The results showed that adding coal increased the population of cultivable soil microorganisms. This increase can be attributed to the following factors:

Improvement in soil physicochemical properties

The addition of coal positively influenced microbial communities by improving soil conditions, which aligns with the findings of Anderson et al. (2011). Similar to biochar, coal may influence key soil properties, including pH, carbon and nitrogen availability, the carbon-to-nitrogen ratio, and cation exchange capacity (CEC) (Kolton et al., 2011; Anderson et al., 2011; Xu et al., 2014). These changes create a more favorable environment for microbial colonization, activity, and diversity, ultimately supporting a healthier and more resilient soil microbiome.

One of the most crucial factors for microbial proliferation is pH regulation because microbial communities are sensitive to acidity and alkalinity. Coal's ability to buffer soil pH may promote the establishment of diverse microbial species, including beneficial bacteria and fungi that contribute to soil fertility. Furthermore, increased carbon availability from coal provides a steady energy source for heterotrophic microorganisms. Improved nitrogen dynamics optimize nutrient cycling and plant-microbe interactions.

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Additionally, coal may enhance CEC, improving nutrient retention and reducing leaching losses. The stabilization of soil nutrients benefits microbial populations by ensuring a continuous supply of essential elements. Together, these modifications reinforce coal's potential as a soil amendment to sustain long-term soil health and microbial stability.

Provide a better habitat for microorganisms.

The porous structure of coal creates a protective refuge for these organisms, shielding them from soil predators and environmental stressors (Gul et al., 2015). This structural advantage promotes microbial survival and proliferation by offering a stable microenvironment. Studies using scanning electron microscopy (SEM) have revealed that the pore sizes in biochar, which typically range from 1 to 15 µm, provide an ideal habitat for diverse microbial communities, including arbuscular mycorrhizal (AM) fungi (Lehmann et al., 2009; Lehmann et al., 2011; Mukherjee et al., 2014). These fungi play a crucial role in soil nutrient cycling by enhancing plant nutrient uptake, particularly phosphorus. The biochar-like properties of coal facilitate phosphorus adsorption on its surface, making phosphorus more available to plants and microorganisms. Additionally, these pores retain moisture and nutrients, creating favorable conditions for microbial colonization and metabolic activity. The presence of these microhabitats within coal particles can foster beneficial microbial interactions, enhancing soil fertility and microbial diversity (Lehmann et al., 2009; Lehmann et al., 2011; Mukherjee et al., 2014).

The carbon content in coal enhances microbial activity by creating an optimal environment for microbial flora (Steinbeiss et al., 2009; Karhu et al., 2011; Zimmerman et al., 2011). Carbon availability influences microbial metabolism because it provides a vital energy source for soil microorganisms, thereby stimulating their growth and enzymatic activity.

Organic carbon is a critical determinant of soil enzymatic processes because it acts as a nutrient reservoir that sustains microbial populations (Wallenius et al., 2011a, 2011b). Incorporating coal into the soil increases stability and carbon retention, which supports long-term microbial proliferation. This study found that applying 50 g of coal per pocket effectively maintains a thriving microbial community (Liang et al., 2010). However, excessive coal application appeared to disrupt the nutrient balance, which could lead to limitations in nitrogen (N) and phosphorus (P), thereby inhibiting microbial activity (Alvarez et al., 2002).

Furthermore, the interaction between carbon-rich amendments, such as coal, and microbial communities can affect biogeochemical cycles, particularly nitrogen and phosphorus dynamics. When excessive carbon is present, microbes may increase nitrogen immobilization, making it less available for plant uptake. Thus, optimizing coal application rates is crucial for balancing microbial enhancement and avoiding nutrient depletion. Both coal and biochar amendments influence the composition of soil biological communities, as observed in Amazonian terra preta soils (O'Neill et al., 2009; Grossman et al., 2010). These amendments have been associated with increases in soil microbial biomass (Liang et al., 2010; O'Neill et al., 2009; Jin, 2010) and higher microbial reproduction rates (Pietikainen et al., 2000; Steiner et al., 2004). Nevertheless, other studies have reported neutral or minor effects on microbial diversity and community structure (Imparato et al., 2016; Jenkins et al., 2016), suggesting that the impact of such amendments may depend on soil type, amendment properties, and environmental conditions.

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Effect of Coal Addition on FDA Enzymatic Activity

The addition of coal significantly increased the enzymatic activity of the FDA compared to the control group (T0 = 1.4 µg fluorescein-h-^{1}-g-^{1} soil vs. T2 = 3.7 µg fluorescein-h-^{1}-g-^{1} soil; TA = 1.9 µg fluorescein-h-^{1}-g-^{1} soil vs. TC = 2.5 µg fluorescein-h-^{1}-g-^{1} soil). In general, coal application affects both the microbial community and soil enzyme activity.

The type of the char used is a critical factor influencing these changes. However, the application rate and the soil environment also play an important role in shaping soil biodiversity (Jenkins et al., 2016; De Tender et al., 2016). Decreases in microbial diversity and enzyme activity were observed at application rates above 75 g, possibly due to nutrient saturation from the coal. The inhibited FDA enzymatic activity was inhibited by increasing nitrogen and phosphorus, as documented by Nannipieri et al. (2011, 2012). Furthermore, differences in enzymatic activity between manure and guano treatments suggest that the type of fertilizer applied may influence soil enzymatic functions as well.

These effects can be attributed to several factors.

Nutrient Cycling of Carbon (C) and Nitrogen (N):

Changes in soil physicochemical properties, such as pH and nutrient availability, play a crucial role in regulating microbial activity. This activity influences the quality and quantity of plant growth. Carbon (C) and nitrogen (N) cycling are fundamental processes that determine soil fertility and microbial health. The balance of these two elements affects microbial metabolism, enzymatic activity, and the structure of the overall soil microbial community.

Carbon is the primary energy source for heterotrophic microorganisms, driving microbial respiration and organic matter decomposition. Meanwhile, nitrogen is essential for microbial protein synthesis and enzymatic functions. The interaction between carbon and nitrogen influences nutrient mineralization and immobilization, which directly impacts plant nutrient availability (Kuzyakov et al., 2000). Applying carbon-rich amendments, such as coal, can alter C/N ratios, which can enhance microbial growth under optimal conditions but potentially limit nitrogen availability when applied excessively (Alvarez et al., 2002).

Furthermore, microbial transformations of carbon and nitrogen contribute to biogeochemical cycles, influencing soil organic matter stability, nitrogen fixation, and greenhouse gas emissions. Maintaining a balanced C/N ratio through appropriate soil amendments is crucial for promoting sustainable soil fertility and enhancing microbial-driven nutrient cycling.

Modification of Soil Habitat:

Adding coal significantly modifies soil habitats due to its unique physical properties, such as its porous structure. Unlike non-carbonized organic matter, coal provides microhabitats that serve as protective refuges for microorganisms, shielding them from environmental stressors and soil predators. This structural advantage increases soil biodiversity and promotes microbial colonization, as observed by Schmidt and Noack (2000).

Coal's high surface area enhances microbial attachment and biofilm formation, facilitating microbial interactions and nutrient exchange. Additionally, its pores help retain moisture and nutrients, creating a more stable environment for microbial communities. These factors

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improve microbial survival, activity, and functional diversity, which ultimately benefits soil fertility and plant health.

Furthermore, microbial hotspots within coal particles foster beneficial interactions between plants and microbes, including symbiotic relationships with arbuscular mycorrhizal (AM) fungi and nitrogen-fixing bacteria. By improving soil aeration, water-holding capacity, and nutrient availability, coal contributes to the long-term stability of soil microbial ecosystems. The enhanced microbial colonization resulting from coal amendment underscores its potential as a sustainable soil conditioner that supports soil health and ecosystem resilience.

These findings align with those of Van Zwieten (2010), who observed increased microbial activity in soybean cultivation after adding biochar (10 t/ha) to ferrallitic soils. Other studies on terra preta soils support the beneficial effects of biochar on soil biological composition and microbial biomass (Kim et al., 2007; O'Neill et al., 2009; Grossman et al., 2010).

IMPLICATION FOR RESEARCH AND PRACTICES

This study emphasizes the importance of carbon-rich amendments, such as coal, for promoting soil biological activity. It demonstrates that these amendments can increase total cultivable microbial populations and overall enzymatic activity, as measured by FDA hydrolysis. Combining cultivable microbial counts with FDA-based measurements provides a robust and accessible framework for assessing microbial responses to soil amendments, especially in areas lacking advanced molecular tools. These results encourage further research on the mechanisms and long-term effects of coal-microbe interactions. They also suggest that coal could be used as a supplementary soil amendment in regions where biochar production is limited by economic or logistical constraints. However, careful evaluation of application rates and environmental implications is essential before broader agricultural implementation.

CONCLUSION

In conclusion, adding coal to ferrallitic soils significantly increased the cultivable microbial flora, highlighting coal's potential as an effective soil amendment. This improvement in microbial diversity was accompanied by a notable increase in FDA enzymatic activity, especially at a rate of 50 g per bag during bean cultivation. These positive effects can be attributed to coal amendment modifying soil physicochemical properties, including changes in pH, nutrient availability, and soil structure. Coal's porous nature likely provides shelter for microorganisms, and its ability to absorb solar radiation may increase soil temperatures and further stimulate microbial activity. These results suggest that coal affects not only microbial biomass but also enhances soil biological activity, which could lead to improved nutrient cycling and soil fertility. Consequently, coal-amended soils could benefit agricultural productivity, especially in regions with ferrallitic soils, which often suffer from nutrient deficiencies and poor microbial activity. These results also imply that coal could be a viable alternative to or addition to traditional organic amendments, such as compost or manure, to improve soil health and plant growth. Further research is needed to investigate the long-term effects of coal applications and optimize its use in different soil types and agricultural practices.

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FUTURE RESEARCH

Future research should emphasize the specific role of black carbon in stimulating soil microbial life, as its effects may differ from those of other carbon amendments. Key directions include:

- Clarifying whether microbial stimulation is linked to the nature of black carbon itself (highly condensed aromatic carbon) rather than to total carbon input.
- Identifying which physical characteristics of black carbon (e.g., porosity, surface area, and particle size) are responsible for enhanced microbial colonization and activity.
- Determining whether black carbon primarily acts as a microbial habitat rather than as a readily available carbon source.
- Comparing different forms of black carbon (e.g., coal and biochar produced at different temperatures) will help determine if similar microbial responses occur.
- Lastly, evaluating the long-term stability of black carbon–microbe interactions in soil systems is essential.

REFERENCES

Adam, G., & Duncan, H. (2001). Development of a sensitive and rapid method for the measurement of total microbial activity using fluorescein diacetate (FDA) in a range of soils. *Soil Biology and Biochemistry, 33*(7–8), 943–951. https://doi.org/10.1016/S0038-0717(00)00244-3

Alvarez, G., Chaussod, R., Cluzeau, D., Godden, B., Lemarié, C., Metzger, L., Nicolardot, B., Parat, J., & Salducci, X. (2002). *Activités biologiques et fertilité des sols : Intérêts et limites des méthodes analytiques disponibles*. INRA.

Anderson, C. R., Condron, L. M., Clough, T. J., Fiers, M., Stewart, A., Hill, R. A., & Sherlock, R. R. (2011). Biochar-induced soil microbial community change: Implications for biogeochemical cycling of carbon, nitrogen, and phosphorus. *Pedobiologia, 54*(5–6), 309–320. https://doi.org/10.1016/j.pedobi.2011.07.003

Bardgett, R. D., & van der Putten, W. H. (2014). Belowground biodiversity and ecosystem functioning. *Nature, 515*(7528), 505–511. https://doi.org/10.1038/nature13855

Clough, T. J., Condron, L. M., Kammann, C., & Müller, C. (2013). A review of biochar and soil nitrogen dynamics. *Agronomy, 3*(2), 275–293. https://doi.org/10.3390/agronomy3020275

De Tender, C. A., Debode, J., Vandecasteele, B., D'Hose, T., Cremelie, P., Haegeman, A., Ruttink, T., Dawyndt, P., & Maes, M. (2016). Biological, physicochemical, and plant health responses in lettuce and strawberry in soil or peat amended with biochar. *Applied Soil Ecology, 107*, 1–12. https://doi.org/10.1016/j.apsoil.2016.05.001

Deenik, J. L., McClellan, T., & Uehara, G. (2010). Charcoal volatile matter content influences plant growth and soil nitrogen transformations. *Soil Science Society of America Journal,*

Article DOI: 10.52589/AJAFS-ILYA4GGD
DOI URL: https://doi.org/10.52589/AJAFS-ILYA4GGD

74(4), 1259–1270. https://doi.org/10.2136/sssaj2009.0115

Grossman, J., O'Neill, B. E., Tsai, S. M., Liang, B., Neves, E., Lehmann, J., & Thies, J. E. (2010). Amazonian Anthrosols support similar microbial communities that differ distinctly from those extant in adjacent, unmodified soils of the same mineralogy. *Microbial Ecology, 60*(1), 192–205. https://doi.org/10.1007/s00248-010-9689-6

Gul, S., Whalen, J. K., Thomas, B. W., Sachdeva, V., & Deng, H. (2015). Physico-chemical properties and microbial responses in biochar-amended soils: Mechanisms and future directions. *Agriculture, Ecosystems & Environment, 206*, 46–59. https://doi.org/10.1016/j.agee.2015.03.015

Imparato, V., Hansen, V., Santos, S. S., Nielsen, T. K., Giagnoni, L., Hauggaard-Nielsen, H., Johansen, A., Renella, G., & Winding, A. (2016). Gasification biochar has limited effects on functional and structural diversity of soil microbial communities in a temperate agroecosystem. *Soil Biology and Biochemistry, 99*, 128–136. https://doi.org/10.1016/j.soilbio.2016.05.004

Jenkins, J. R., Viger, M., Arnold, E. C., Harris, Z. M., Ventura, M., Miglietta, F., Girardin, C., Edwards, D., & Rumpel, C. (2016). Biochar alters the soil microbiome and soil function: Results of next-generation amplicon sequencing across Europe. *GCB Bioenergy, 9*(2), 591–612. https://doi.org/10.1111/gcbb.12371

Jin, H. (2010). *Characterization of microbial life colonizing biochar and biochar-amended soils* (Doctoral dissertation, Cornell University). https://ecommons.cornell.edu/

Karhu, K., Mattila, T., Bergström, I., & Regina, K. (2011). Biochar addition to agricultural soil increased CH_4 uptake and water holding capacity—Results from a short-term pilot field study. *Agriculture, Ecosystems & Environment, 140*(1–2), 309–313. https://doi.org/10.1016/j.agee.2011.01.005

Kolton, M., Meller Harel, Y., Pasternak, Z., Graber, E. R., Elad, Y., & Cytryn, E. (2011). Impact of biochar application to soil on the root-associated bacterial community structure of fully developed greenhouse pepper plants. *Applied and Environmental Microbiology, 77*(14), 4924–4930. https://doi.org/10.1128/AEM.00148-11

Krull, E. S., Skjemstad, J. O., & Baldock, J. A. (2004). *Functions of soil organic matter and the effect on soil properties*. GRDC.

Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C., & Crowley, D. (2011). Biochar effects on soil biota—A review. *Soil Biology and Biochemistry, 43*(9), 1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.022

Liang, B., Lehmann, J., Sohi, S. P., Thies, J. E., O'Neill, B., Trujillo, L., Gaunt, J., Solomon, D., Grossman, J., Neves, E. G., & Luizão, F. J. (2010). Black carbon affects the cycling of non-black carbon in soil. *Organic Geochemistry, 41*(2), 206–213. https://doi.org/10.1016/j.orggeochem.2009.09.007

Liu, S., Zhang, Y., Zong, Y., Hu, Z., Wu, S., Zhou, J., Jin, Y., & Zou, J. (2016). Response of soil carbon dioxide fluxes, soil organic carbon, and microbial biomass carbon to biochar amendment: A meta-analysis. *GCB Bioenergy, 8*(2), 392–406. https://doi.org/10.1111/gcbb.12265

O'Neill, B., Grossman, J., Tsai, S. M., Gomes, J. E., Lehmann, J., Peterson, J., Neves, E., & Thies, J. E. (2009). Bacterial community composition in Brazilian Anthrosols and

Article DOI: 10.52589/AJAFS-ILYA4GGD
DOI URL: https://doi.org/10.52589/AJAFS-ILYA4GGD

adjacent soils characterized using culturing and molecular identification. *Microbial Ecology, 58*(1), 23–35. https://doi.org/10.1007/s00248-009-9505-9

Pietikainen, J., Kiikkilä, O., & Fritze, H. (2000). Charcoal as a habitat for microbes and its effect on the microbial community of the underlying humus. *Oikos, 89*(2), 231–242. https://doi.org/10.1034/j.1600-0706.2000.890203.x

Schloter, M., Dilly, O., & Munch, J. C. (2003). Indicators for evaluating soil quality. *Agriculture, Ecosystems & Environment, 98*(1–3), 255–262. https://doi.org/10.1016/S0167-8809(03)00085-9

Schmidt, M. W. I., & Noack, A. G. (2000). Black carbon in soils and sediments: Analysis, distribution, implications, and current challenges. *Global Biogeochemical Cycles, 14*(3), 777–793. https://doi.org/10.1029/1999GB001208

Steinbeiss, S., Gleixner, G., & Antonietti, M. (2009). Effect of biochar amendment on soil carbon balance and soil microbial activity. *Soil Biology and Biochemistry, 41*(6), 1301–1310. https://doi.org/10.1016/j.soilbio.2009.03.016

Steiner, C., Teixeira, W. G., Lehmann, J., & Zech, W. (2004). Microbial response to charcoal amendments of highly weathered soils and Amazonian dark earths. In B. Glaser & W. I. Woods (Eds.), *Amazonian dark earths: Explorations in space and time* (pp. 195–212). CRC Press.

Van Zwieten, L., Kimber, S., Morris, S., Chan, K. Y., Downie, A., Rust, J., Joseph, S., & Cowie, A. (2010). Effects of biochar from slow pyrolysis of paper mill waste on agronomic performance and soil fertility. *Plant and Soil, 327*(1–2), 235–246. https://doi.org/10.1007/s11104-009-0050-x

Wallenius, K., Niemi, R. M., & Rita, H. (2011a). Using stratified sampling based on pre-characterization of samples in soil microbiological studies. *Applied Soil Ecology, 51*, 111–113. https://doi.org/10.1016/j.apsoil.2011.09.003

Wallenius, K., Rita, H., Mikkonen, A., Lappi, K., Lindström, K., Hartikainen, H., Raateland, A., & Niemi, R. M. (2011b). Effects of land use on the level, variation, and spatial structure of soil enzyme activities and bacterial communities. *Soil Biology and Biochemistry, 43*(7), 1464–1473. https://doi.org/10.1016/j.soilbio.2011.03.018

Zimmerman, A. R., Gao, B., & Ahn, M.-Y. (2011). Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. *Soil Biology and Biochemistry, 43*(6), 1169–1179. https://doi.org/10.1016/j.soilbio.2011.02.005

Article DOI: 10.52589/AJAFS-ILYA4GGD
DOI URL: https://doi.org/10.52589/AJAFS-ILYA4GGD