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Research Article

CO₂ emission in soil under eucalyptus cultivation with biochar application[1]

Chansislayne Gabriela da Silva[2], Renato Ribeiro Passos[2],
Danilo Andrade Santos[2], Eduardo de Sá Mendonça[2], Lorena Contarini Machado[2]

ABSTRACT

The use of biochar to fix carbon in the long term has become promising for reducing CO_2 emissions, with eucalyptus bark being an excellent source of raw material for its production. This study aimed to evaluate the effect of applying eucalyptus bark biochar on soil CO_2 emissions, in an area planted with eucalyptus. A randomized block design, with a 2 x 5 factorial scheme, was used, encompassing two pyrolysis temperatures (350 and 600 ºC) and five biochar doses (0, 0.625, 1.25, 2.5 and 5 Mg ha^{-1}), with three replications, where the doses corresponded to 25 % of the dose used at planting. The soil CO_2 emissions, humidity and temperature were measured at 90, 97, 105, 112, 120 and 127 days of surface application of biochar. The 5 Mg ha^{-1} dose contributed to reduce the accumulated CO_2 emissions by 65 and 24 %, respectively for the pyrolysis temperatures of 350 and 600 ºC, when compared to the 0 Mg ha^{-1} dose, thus contributing to mitigate emissions and support agricultural and environmental sustainability. In order to reduce the CO_2 flow, the period indicated for its application is when the soil temperature is higher and the soil humidity is lower.

KEYWORDS: Eucalyptus biochar, slow pyrolysis, forest residues, CO_2 mitigation.

RESUMO

Emissão de CO_2 em solo sob cultivo de eucalipto com aplicação de biocarvão

O uso de biocarvão para fixar carbono a longo prazo tem se tornado promissor para a redução de emissões de CO_2, sendo a casca de eucalipto uma excelente fonte de matéria-prima para a sua produção. Objetivou-se avaliar o efeito da aplicação de biocarvão de casca de eucalipto nas emissões de CO_2 do solo, em área plantada com eucalipto. Utilizou-se delineamento em blocos casualizados, em esquema fatorial 2 x 5, sendo duas temperaturas de pirólise (350 e 600 ºC) e cinco doses de biocarvão (0; 0,625; 1,25; 2,5; e 5 Mg ha^{-1}), com três repetições, onde as doses corresponderam a 25 % da dose utilizada no plantio. Após 90, 97, 105, 112, 120 e 127 dias da aplicação superficial do biocarvão, foram avaliadas as emissões de CO_2, umidade e temperatura do solo. A dose de 5 Mg ha^{-1} contribuiu para a diminuição da emissão de CO_2 acumulado em 65 e 24 % nas temperaturas de pirólise de 350 e 600 ºC, respectivamente, em comparação com a dose de 0 Mg ha^{-1}, assim contribuindo para a mitigação de emissões e promovendo a sustentabilidade agrícola e ambiental. A fim de reduzir o fluxo de CO_2, o período indicado para sua aplicação é quando a temperatura do solo está mais elevada e a umidade do solo mais baixa.

PALAVRAS-CHAVE: Biochar de eucalipto, pirólise lenta, resíduo florestal, mitigação de CO_2.

INTRODUCTION

Climate change and increased atmospheric CO_2 are globally pressing concerns. CO_2 emissions are among the primary contributors to global warming (Shoudho et al. 2024). In agricultural settings, the CO_2 release into the soil may result from organic matter decomposition or inadequate management practices. However, sustainable practices such as biochar application have shown potential to reduce CO_2 emissions, enhance carbon sequestration and improve soil health (Li et al. 2018).

Biochar is a solid product generated through the pyrolysis of various types of biomasses, including agricultural residues such as rice straw, coffee husk and sugarcane bagasse; forestry residues such as sawdust, branches and bark; and urban waste, such as sewage sludge and food waste (Fernandes et al. 2020). These materials are selected based on their availability, low cost and environmental benefits. Moreover, much of this waste is often not adequately disposed of or recycled (Singh et al. 2022). During pyrolysis, biomass is heated in an anaerobic or anoxic environment at temperatures ranging from 300 to

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[2] Universidade Federal do Espírito Santo, Departamento de Agronomia, Alegre, ES, Brazil. *E-mail/ORCID*: chansislayne_silva@outlook.com/0009-0001-0915-0844; renatoribeiropassos@gmail.com/0000-0001-7730-748X; danilo_as@live.com/0000-0002-3046-8945; esmjplia@gmail.com/0000-0003-3284-7129; contarini.machado@gmail.com/0000-0002-8126-167X.

1,000 ºC, transforming it into a highly stable material resistant to thermal and chemical degradation, as well as photo-oxidation (Futa et al. 2020).

The forestry sector generates a substantial amount of waste with high potential for biochar production. In 2018, the sector produced approximately 52 million tons of waste, including 36.11 million tons from bark, branches and leaves, with eucalyptus constituting 76 % of this production (IBÁ 2023). Therefore, eucalyptus bark is particularly promising as a biochar feedstock.

Research indicates that eucalyptus biochar can improve soil properties by acting as a soil conditioner and enhancing its physical, chemical, biological and hydrological characteristics (Lei & Zhang 2013, Reichert et al. 2023). Biochar also has potential to reduce soil CO_2 emissions, thereby contributing to carbon sequestration and cleaner energy generation (Butphue & Kaewpradit 2022). These effects are associated with the biochar's capacity to retain organic carbon and stabilize soil carbon stocks, due, in part, to its large surface area and porosity, which effectively minimize CO_2 emissions (Lehmann 2007).

Additionally, the biochar application can positively influence the soil microbiology, supporting or enhancing soil quality and nutrient cycling (Zhang et al. 2023). Soil CO_2 emissions primarily originate from root respiration and organic matter decomposition facilitated by microorganisms (Wu et al. 2022). Factors such as soil moisture and temperature significantly affect CO_2 emissions, as increases in these variables can stimulate microbial activity (Yerli et al. 2022).

Although extensive research exists on biochar production and its effects on soil quality, relatively few studies have examined how the pyrolysis temperature of eucalyptus waste and varying biochar application rates impact soil CO_2 emissions. Therefore, this study aimed to evaluate the effects of eucalyptus bark biochar on soil CO_2 emissions in a eucalyptus cultivation area.

MATERIAL AND METHODS

This study was conducted at the experimental area of the Instituto Federal do Espírito Santo, located in the Rive district, in Alegre, Espírito Santo state, Brazil (20º46'08"S, 41º27'15"W and altitude of 131 m).

The region's climate is classified as Aw under the Köppen-Geiger classification, characterized by a tropical climate with hot, rainy summers and dry winters. During the experimental period, monthly rainfall and temperature data were collected from a weather station near the experimental site (Figure 1).

The eucalyptus bark used for pyrolysis was sourced from plantation processing waste in southern Espírito Santo state. The material, provided by Usina Bragança, was uniformly chopped and dried. It was then carbonized in a pyrolysis reactor for 60 min, at final temperatures of either 350 or 600 ºC, producing biochar with varying properties and analyzed using a slow pyrolysis technique.

After pyrolysis, the biochar was ground in a knife mill and then sieved to 0.5 mm. The raw material and biochar were characterized by determining the C, H, O and N contents, using an elemental analyzer (PerkinElmer 2400 Series II CHNS/O). Levels of N, P, K, Ca, Mg, Cu, Fe, Mn and Zn were measured by incinerating samples in a muffle furnace (550 ºC for 4 hours), solubilizing the ashes in 0.5 mol L^{-1} of HCl, and analyzing the solution with an inductively coupled plasma spectrophotometer (ICPS). The pH was measured in water solution (1:20 ratio) (Tables 1, 2 and 3).

The area's history includes use as buffalo pasture in 2011, followed by goat breeding in 2013. Pasture management included soil acidity correction, fertilization and irrigation maintenance. Eucalyptus was introduced in March 2018, when the area was plowed and cleared. Planting was carried out with a spacing of 3 m between rows and 2 m between plants, in a 2,640 m^2 area. Each experimental block included a planting row without biochar application as a control, forming the experiment's border. Six

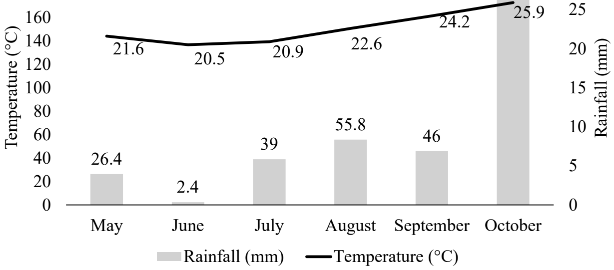

Figure 1. Accumulated monthly rainfall and average temperature recorded in the experimental area from May to October 2023 (Rive district, Alegre, Espírito Santo state, Brazil).

Eucalyptus urograndis plants were arranged in predesignated rows in each block.

A randomized block design, with three replications, was used, structured as a 2 x 5 factorial scheme: two pyrolysis temperatures (350 and 600 ºC) for producing eucalyptus bark biochar and five biochar doses (0, 0.0625, 0.125, 0.25 and 0.5 % by volume), based on the soil volume in the planting furrow, corresponding to application rates of 0, 0.625, 1.25, 2.5 and 5 Mg ha^{-1}, respectively (Figure 2). The biochar was applied in furrows (30 cm deep and 60 cm wide), before planting.

Soil samples were collected at a depth of 0-30 cm before planting eucalyptus, in 2018. Table 4 shows the soil chemical properties, being medium textured, with 68, 7 and 25 % of total sand, silt and clay, respectively.

A second biochar application was conducted in May 2023, 5 years and 2 months after the initial application at planting. The second dose was set at 25 % of the initial biochar volume. Unlike the initial application, which was incorporated during planting, this second application was surface-applied and lightly scarified with a garden rake to a depth of 5 cm.

Soil CO_2 emissions were measured using a flow chamber and portable analyzer (LI-8100, Li-Cor, USA). PVC rings (10 cm in diameter) were placed on the soil surface (5 cm deep) between the third and fourth plants of each treatment in each plot. Measurements were taken at 90, 97, 105, 112, 120 and 127 days after biochar application in September and October 2023, between 8:00 and 10:00 a.m. Soil temperature and moisture were measured

Table 1. Characteristics of eucalyptus bark used as raw material for biochar production.

pH	Ca	Mg	K	P	CEC	C	N	H	O	H/C	O/C
	g kg^{-1}				cmol$_c$ kg^{-1}	%					
4.73	4.76	0.29	15.00	0.32	375.9	39.72	0.43	5.28	54.57	1.03	1.03

CEC: cation exchange capacity.

Table 2. Macro and micronutrient contents[1] in eucalyptus bark biochar produced at pyrolysis temperatures of 350 and 600 ºC.

Variable	pH	P	K	Ca	Mg	Cu	Fe	Zn	Mn
		g kg^{-1}				mg kg^{-1}			
350 ºC	7.1	0.07	0.57	2.64	0.41	7.20	2,605	19.15	557.1
600 ºC	8.1	0.09	0.70	3.31	0.57	36.35	3,088	37.70	819.6

[1] Obtained by nitric-perchloric digestion (Teixeira et al. 2017).

Table 3. Elemental composition[1] of C, H, N and O and the corresponding C/N, H/C and O/C ratios in eucalyptus bark biochar produced at pyrolysis temperatures of 350 and 600 ºC.

Temperature	C	H	N	O	C/N	H/C	O/C
	Elemental content (%)						
350 ºC	54.99	3.12	0.60	41.28	107.01	0.65	0.56
600 ºC	65.05	1.44	0.51	34.37	149.80	0.26	0.38

[1] Determined on a Perkin Elmer Series II 2400 analyzer; O (%) = 100 - C - H - N.

Table 4. Chemical characterization[1] of the soil used in establishing the eucalyptus experiment.

pH (H_2O)	P	K	Na	Ca	Mg	Al	H + Al	T	SB	V
	mg dm^{-3}			cmol$_c$ dm^{-3}						%
5.88	13.64	125.00	6.00	2.30	1.01	0.00	2.58	6.25	3.66	58.40

[1] Parameters measured as follows: pH in H_2O (1:2.5 ratio); K, Na: exchangeable potassium and sodium, determined by flame photometry after extraction with Mehlich-1 solution; Ca, Mg: exchangeable calcium and magnesium, extracted with potassium chloride and analyzed by atomic absorption spectrometry; Al: exchangeable aluminum, extracted with potassium chloride and quantified by titration; H + Al: potential acidity, determined by calcium acetate extraction and titration; P: phosphorus content, measured by colorimetry, following Mehlich-1 extraction; SB (sum of bases): obtained by summing the concentrations of Ca + Mg + Na + K; T (potential cation exchange capacity): calculated as (K/390) + (Na/230) + Ca + Mg + (H + Al) (Teixeira et al. 2017).

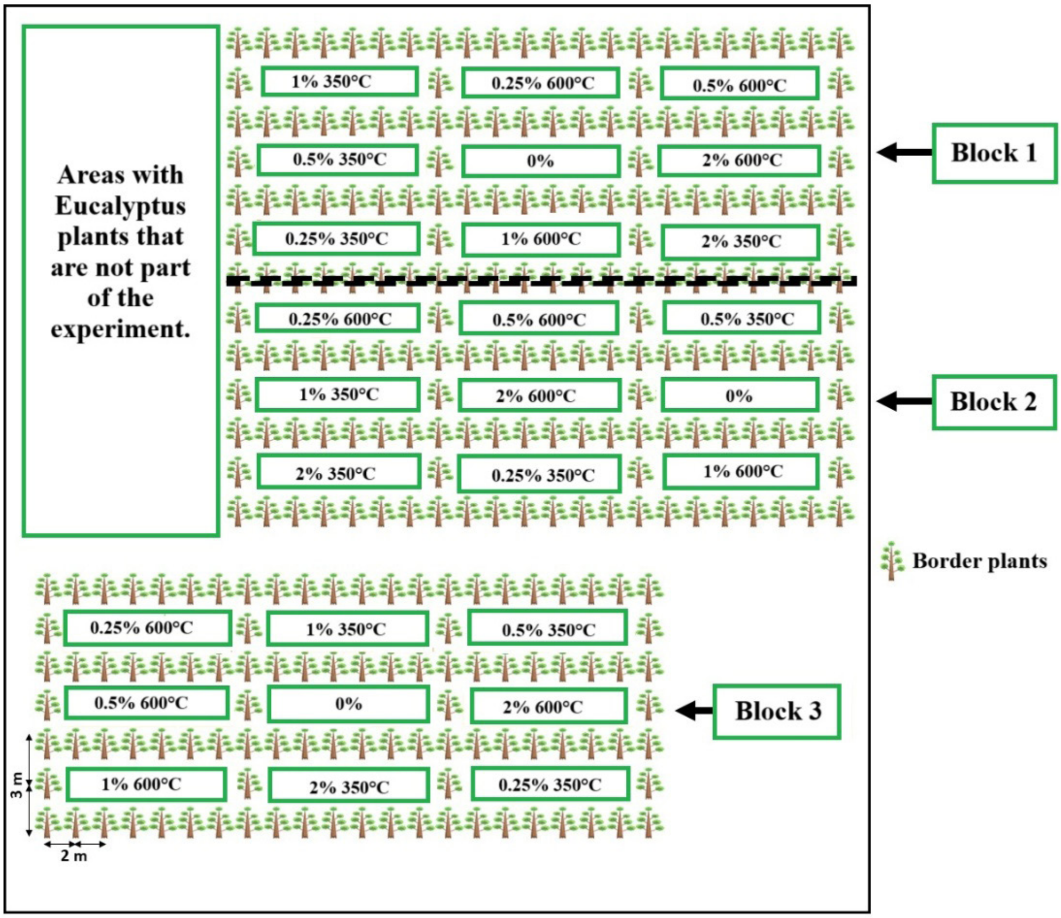

Figure 2. Layout of the study area, showing the spatial distribution of treatments within each planting block.

near the ring, using a portable Frequency Domain Reflectometry (FDR) device.

To analyze data variability, descriptive statistics, including mean and standard deviation, were calculated to understand the central tendency and dispersion of the collected values. Pearson's correlation analysis was performed to assess the linear relationship between variables, and statistical analyses were conducted in R (R Core Team 2018).

RESULTS AND DISCUSSION

Between 90 and 127 days following the surface application of biochar, CO_2 emissions were higher, on average, for the biochar produced at a pyrolysis temperature of 350 ºC (12.85 µmol m^{-2} s^{-1}) than for that produced at 600 ºC (11.36 µmol m^{-2} s^{-1}) (Figure 3). Specifically, the maximum dose of biochar at 350 ºC yielded lower cumulative CO_2 emissions over time, if compared to other doses. In contrast, for the biochar at 600 ºC, cumulative CO_2 emissions over 127 days were the highest ones at doses of 0 and 1.25 Mg ha^{-1}, with other doses (0.625, 2.5 and 5 Mg ha^{-1}) showing comparable values. Notably, the CO_2 emissions at the highest dose (5 Mg ha^{-1}) were similar for both pyrolysis temperatures (350 and 600 ºC).

The 5 Mg ha^{-1} biochar dose led to cumulative CO_2 emission reductions of 65 and 24 % over 127 days at 350 and 600 ºC, respectively, when compared to the control (0 Mg ha^{-1}). This trend suggests a dose-dependent effect of biochar on organic matter decomposition and CO_2 release. At moderate doses, biochar seems to stimulate microbial activity, enhancing organic matter decomposition and CO_2 release. Conversely, at higher doses, CO_2 emissions decrease, potentially due to microbial activity inhibition. Similar findings by Wang et al. (2021) indicate that rice straw biochar forms organo-mineral complexes that gradually reduce CO_2 emissions.

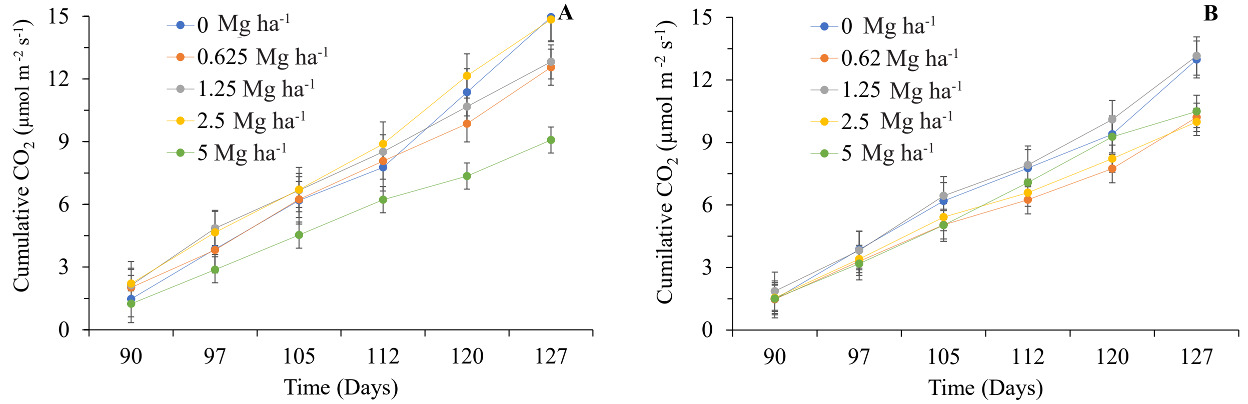

Figure 3. Cumulative CO_2 emissions as influenced by biochar application at pyrolysis temperatures of 350 (A) and 600 ºC (B).

Additionally, Wu et al. (2022) reported that biochar can decrease microbial activity, subsequently reducing soil CO_2 emissions. The results of this study reinforce that higher biochar doses contribute to reduced CO_2 emissions. A key factor may be the high C/N ratio of biochar (107.01 at 350 ºC and 149.80 at 600 ºC), which restricts microbial activity due to low nitrogen availability. Biochar produced at 600 ºC, with a C/N ratio 40 % higher than at 350 ºC, showed smaller CO_2 emission variations across doses of 0.625, 1.25 and 2.5 Mg ha^{-1}, with reductions of 20.05, 5.18 and 28.89 %, respectively.

Zimmerman et al. (2011) observed that biochar produced at lower temperatures increases CO_2 emissions by enhancing microbial activity (positive priming effect), whereas high-temperature biochar emits less CO_2, possibly due to greater recalcitrance and reduced reactivity. The biochar produced at 600 ºC showed lower O/C and H/C ratios than that at 350 ºC, suggesting less chemical reactivity in the soil.

The standard error analysis showed the data variability, especially at higher doses, suggesting that the effects of biochar on CO_2 accumulation may vary with environmental or biological factors. Soil temperature, for example, was inversely correlated with CO_2 emissions at both 600 and 350 ºC biochar applications, with correlation coefficients of -0.8757 and -0.5321, respectively, indicating lower CO_2 emissions as the soil temperature rose (Figure 4).

Biochar application reduces CO_2 emissions by stabilizing organic matter, regulating microbial activity and improving moisture retention and soil chemistry (Shoudho et al. 2024). These effects help to reduce organic matter decomposition and CO_2 release, particularly under temperature fluctuations (Lehmann et al. 2021). Figueiredo et al. (2019) observed that biochar produced at low temperatures (300-400 ºC) increases CO_2 emissions, whereas biochar produced at higher temperatures (≥ 500 ºC) decreases it. This aligns with the finding that biochar at 600 ºC is more effective in reducing CO_2 emissions, likely due to the adsorption and stabilization of organic compounds via its extensive surface area and carbon content.

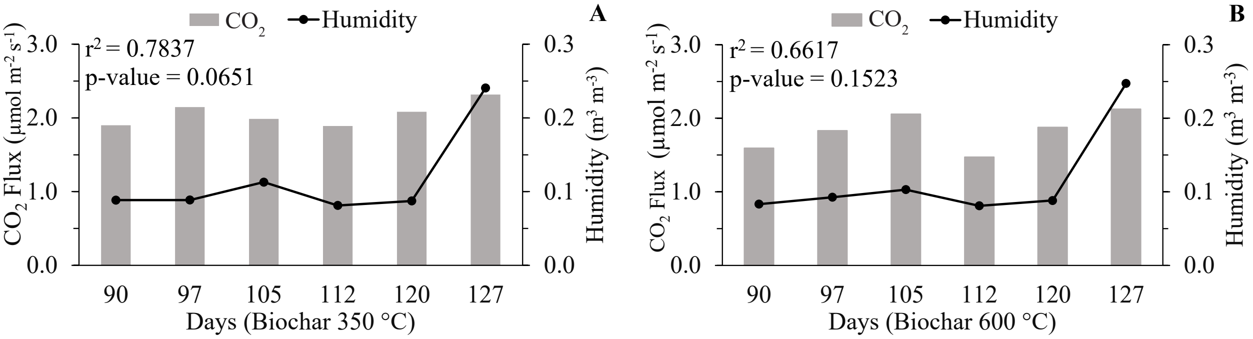

Figure 4. Mean soil temperature and CO_2 emissions across evaluation periods for biochar produced at pyrolysis temperatures of 350 (A) and 600 ºC (B).

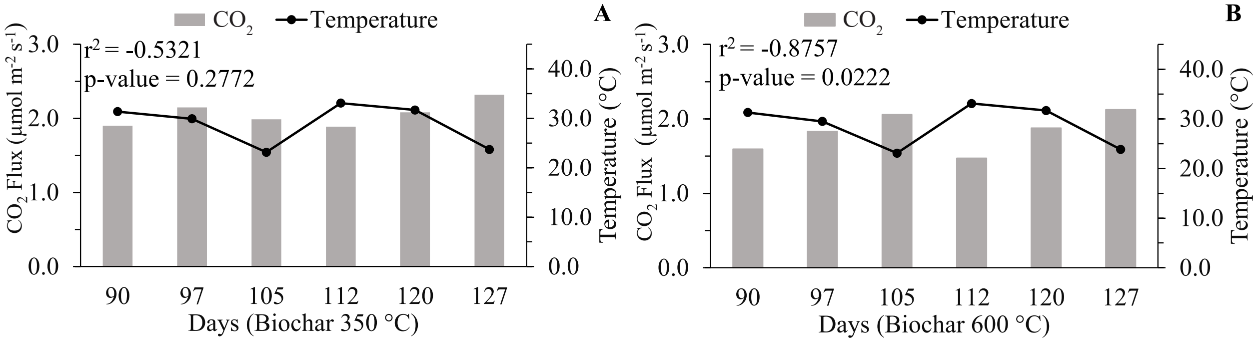

Figure 5. Average soil moisture values in relation to CO_2 emissions from biochar produced at pyrolysis temperatures of 350 (A) and 600 ºC (B).

The rate of biochar decomposition is influenced by climate, particularly temperature and humidity (Yerli et al. 2022). Dilekoglu & Sakin (2017) identified CO_2 emissions as being primarily affected by soil organic matter, plant residue and soil organisms. Soil moisture and CO_2 emissions displayed a positive correlation of 78.37 and 66.17 % for biochar at 350 and 600 ºC, respectively, over the 90-127-day study period (Figure 5).

The soil water potential directly impacts transpiration and, thus, CO_2 emissions (Reichert et al. 2023). Rittl et al. (2018) found that eucalyptus biochar applied at 400-600 ºC increased CO_2 emissions when the soil was at the field capacity and decreased emissions when the field capacity was below 60 %. This outcome may result from the biochar influence on the soil structure, porosity and water retention, which affect microbial respiration and CO_2 release, as microorganisms need water for metabolic processes. Therefore, a reduced microbial activity during dry periods could inhibit CO_2 emissions.

The Wang et al. (2016) meta-analysis also found a positive association between soil moisture and CO_2 emissions, supporting the strategy of biochar application under dry conditions to stabilize CO_2 emissions. Farrell et al. (2013) showed that high-temperature biochar (like those from eucalyptus and wheat) are more recalcitrant due to their aromatic structure, making them less susceptible to microbial oxidation. This may explain the lower mean CO_2 emissions observed with 600 ºC biochar in this study. Similarly, Rittl et al. (2020) found that biochar from *Miscanthus giganteus* slowed organic matter decomposition, reducing CO_2 emissions over a 144-day period, being consistent with this study's findings.

CONCLUSIONS

1. The surface application of eucalyptus bark biochar effectively reduces soil CO_2 emissions, making it a promising strategy for carbon sequestration;
2. Biochar produced at a pyrolysis temperature of 600 ºC shows a lower average CO_2 emission variability, when compared to that produced at 350 ºC, suggesting a greater stability and efficacy in reducing emissions;
3. Applying biochar during periods of high temperature and low soil moisture may further decrease CO_2 emissions, contributing to climate change mitigation, while promoting both agricultural productivity and environmental sustainability.

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REFERENCES

BUTPHU, S.; KAEWPRADIT, W. Impacts of eucalyptus biochar application on greenhouse gas emission from an upland rice-sugarcane cropping system on sandy soil. *Experimental Agriculture*, v. 58, e25, 2022.

DILEKOGLU, M. F.; SAKIN, E. Effect of temperature and humidity in soil carbon dioxide emission. *Journal of Animal & Plant Sciences*, v. 27, n. 5, p. 1596-1603, 2017.

FARRELL, M.; KUHN, T. K.; MACDONALD, L. M.; MADDERN, T. M.; MURPHY, D. V.; HALL, P. A.; SINGH, B. P.; BAUMANN, K.; KRULL, E. S.;

BALDOCK, J. A. Microbial utilisation of biochar-derived carbon. *Science of the Total Environment*, v. 465, n. 1, p. 288-297, 2013.

FERNANDES, B. C.; OLIVEIRA, J.; DIAS JÚNIOR, A. F.; OLIVEIRA, V. P.; TEÓFILO, T. M. S; OLIVEIRA, A.; OLIVEIRA, V.; SOUZA, M. F.; SILVA, D. V. Impact of pyrolysis temperature on the properties of eucalyptus wood-derived biochar. *Materials*, v. 13, n. 24, e5841, 2020.

FIGUEIREDO, C. C. D.; COSER, T. R.; MOREIRA, T. N.; LEÃO, T. P.; VALE, A. T. D.; PAZ-FERREIRO, J. Carbon mineralization in a soil amended with sewage sludge-derived biochar. *Applied Sciences*, v. 9, n. 21, e4481, 2019.

FUTA, B.; OLESZCZUK, P.; ANDRUSZCZAK, S.; KWIECIŃSKA-POPPE, E.; KRASKA, P. Effect of natural aging of biochar on soil enzymatic activity and physicochemical properties in long-term field experiment. *Agronomy*, v. 10, n. 3, e449, 2020.

INDÚSTRIA BRASILEIRA DE ÁRVORES (IBÁ). *Relatório anual 2023*: IBÁ. 2023. Available at: https://iba.org/datafiles/publicacoes/relatorios/relatorio-anual-iba2023-r.pdf. Access on: Dec. 26, 2023.

LEHMANN, J. A handful of carbon. *Nature*, v. 447, n. 7141, p. 143-144, 2007.

LEHMANN, J.; COWIE, A.; MASIELLO, C. A.; KAMMANN, C.; WOOLF, D.; AMONETTE, J. E.; CAMPS-ARBESTAIN, T.; WHITMAN, T. Biochar in climate change mitigation. *Nature Geoscience*, v. 14, n. 12, p. 883-892, 2021.

LEI, O.; ZHANG, R. Effects of biochar derived from different feedstocks and pyrolysis temperature on soil physical and hydraulic properties. *Journal of Soil and Sediments*, v. 13, n. 9, p. 1561-1572, 2013.

LI, Y.; HU, S.; CHEN, J.; MÜLLER, K.; LI, Y.; FU, W.; LIN, Z.; WANG, H. Effects of biochar application in forest ecosystems on soil properties and greenhouse gas emissions: a review. *Journal of Soils and Sediments*, v. 18, n. 2, p. 546-563, 2018.

R CORE TEAM. *R*: a language and environment for statistical computing. Vienna: R Foundation for Statistical Computing, 2018.

REICHERT, J. M.; MORALES, B.; LIMA, E. M.; BASTOS, F.; MORALES, C. A. S.; ARAÚJO, E. F. Soil morphological, physical and chemical properties affecting *Eucalyptus* spp. productivity on Entisols and Ultisols. *Soil and Tillage Research*, v. 226, e105563, 2023.

RITTL, T. F.; BUTTERBACH-BAHL, K.; BASILE, C. M.; PEREIRA, L. A.; ALMS, V.; DANNENMANN, M.; COUTO, E. G.; CERRI, C. E. Greenhouse gas emissions from soil amended with agricultural residue biochars: effects of feedstock type, production temperature and soil moisture. *Biomass and Bioenergy*, v. 117, n. 1, p. 1-9, 2018.

RITTL, T. F.; CANISARES, L.; SAGRILO, E.; BUTTERBACH-BAHL, K.; DANNENMANN, M.; CERRI, C. E. Temperature sensitivity of soil organic matter decomposition varies with biochar application and soil type. *Pedosphere*, v. 30, n. 3, p. 336-342, 2020.

SHOUDHO, K. N.; KHAN, T. H.; ARA, U. R.; KHAN, M. R.; SHAWON, Z. B. Z.; HOQUE, M. E. Biochar in global carbon cycle: towards sustainable development goals. *Current Research in Green and Sustainable Chemistry*, v. 8, e100409, 2024.

SINGH, H.; NORTHUP, B. K.; RICE, C. W.; PRASAD, P. V. Biochar applications influence soil physical and chemical properties, microbial diversity, and crop productivity: a meta-analysis. *Biochar*, v. 4, e8, 2022.

TEIXEIRA, P. C.; DONAGEMMA, G. K.; FONTANA, A.; TEIXEIRA, W. G. *Manual de métodos de análise de solo*. 3. ed. Brasília, DF: Embrapa, 2017.

WANG, J.; XIONG, Z.; KUZYAKOV, Y. Biochar stability in soil: meta-analysis of decomposition and priming effects. *Global Change Biology Bioenergy*, v. 8, n. 3, p. 512-523, 2016.

WANG, W.; ZHU, X.; CHANG, L.; ZHANG, Y.; ZHANG, S.; WU, D. How do earthworms affect the soil organic carbon fractions and CO_2 emissions after incorporation of different maize straw-derived materials. *Journal of Soils and Sediments*, v. 21, n. 1, p. 3632-3644, 2021.

WU, W.; HAN, J.; GU, Y.; LI, T.; XU, X.; JIANG, Y.; CHENG, K. Impact of biochar amendment on soil hydrological properties and crop water use efficiency: a global meta-analysis and structural equation model. *Global Change Biology Bioenergy*, v. 14, n. 6, p. 657-668, 2022.

YERLI, C.; CAKMAKCI, T.; SAHIN, U. CO_2 emissions and their changes with H_2O emissions, soil moisture, and temperature during the wetting-drying process of the soil mixed with different biochar materials. *Journal of Water and Climate Change*, v. 13, n. 12, p. 4273-4282, 2022.

ZHANG, C.; ZHAO, X.; LIANG, A.; LI, Y.; SONG, Q.; LI, X.; LI, D.; HOU, N. Insight into the soil aggregate-mediated restoration mechanism of degraded black soil via biochar addition: emphasizing the driving role of core microbial communities and nutrient cycling. *Environmental Research*, v. 228, e115895, 2023.

ZIMMERMAN, A. R.; GAO, B.; AHN, M. Y. Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. *Soil Biology and Biochemistry*, v. 43, n. 26, p. 1169-1179, 2011.