



THIAGO COSTA VIANA

**MANAGEMENT OF ORGANIC RESIDUES IN THE COFFEE
PRODUCTION CHAIN AND THEIR IMPACT ON SOIL
ATTRIBUTES FOR THE PROMOTION OF CIRCULAR
ECONOMY**

**LAVRAS – MG
2025**

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Dissertação apresentada à
Universidade Federal de Lavras, como
parte das exigências do programa de Pós-
Graduação em Ciência do Solo, área de
concentração Fertilidade do Solo e
Nutrição de Plantas, para a obtenção do
título de Mestre.

Dr. Leônidas Carrijo Azevedo Melo
Orientador

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THIAGO COSTA VIANA

**GESTÃO DE RESÍDUOS ORGÂNICOS NA CADEIA PRODUTIVA DO CAFÉ
E SEU IMPACTO NOS ATRIBUTOS DO SOLO PARA PROMOÇÃO DA ECONOMIA
CIRCULAR**

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UFLA
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**LAVRAS - MG
2025**

*A Deus e Maria Santíssima;
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pelo apoio, amor e suporte incondicional;
As minhas sobrinhas Nicolle Viana e Ana Laura Viana ;
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*“Não fui eu que ordenei a você? Seja forte e corajoso!
Não se apavore nem desanime,
pois o SENHOR, o seu Deus,
estará com você por onde você andar” Josué 1:9 .*

RESUMO GERAL

O aumento da população exige maior produção agrícola, o que, por sua vez, gera consideráveis quantidades de resíduos orgânicos, incluindo resíduos agrícolas. Uma porção significativa desses resíduos agrícolas origina-se dos processos de colheita e pós-colheita. No Brasil, a cadeia produtiva do café desempenha um papel econômico significativo em nível nacional e global, mas também gera resíduos subutilizados. No contexto de uma economia circular, a transformação desses resíduos orgânicos possibilita sua reutilização na agricultura. Técnicas como compostagem, fermentação anaeróbia e pirólise podem ser aplicadas para o manejo dos resíduos provenientes da produção de café. A aplicação de produtos derivados desses processos, conhecidos como condicionadores de solo, pode aumentar a eficiência dos fertilizantes convencionais e melhorar a saúde do solo em comparação aos sistemas de manejo convencional. O objetivo deste estudo foi comparar os efeitos condicionadores no solo da casca de café, composto orgânico, Bokashi, biochar e COMBI (composto + biochar) na cultura do cafeeiro em duas áreas (empresarial e familiar) produtoras de café no município de Santo Antônio do Amparo, MG, ao longo de duas safras agrícolas (2021/2022 e 2022/2023). O biochar foi produzido por meio da pirólise da casca e da madeira do cafeeiro, enquanto o composto e o Bokashi foram obtidos principalmente da casca de café como resíduo principal. Esses materiais foram caracterizados quimicamente. Os tratamentos avaliados foram: 1) casca de café *in natura*, 2) composto orgânico, 3) Bokashi, 4) biochar (casca e madeira do cafeeiro), 5) COMBI, 6) fertilizante organomineral comercial, 7) fertilização convencional. As doses de aplicação dos condicionadores de solo variaram entre 5 e 10 toneladas por hectare. Os tratamentos 1 a 5 receberam fertilização mineral convencional como complemento nutricional. O experimento foi conduzido em delineamento de blocos casualizados com quatro repetições. Foram realizadas análises de solo, análises foliares, avaliação de bioindicadores do solo e análise da produtividade do cafeeiro. Para os atributos químicos foram verificadas diferenças significativas em relação ao controle na área empresarial 2021/2022 para: cálcio e magnésio sob o uso de COMBI, as concentrações foram superiores em 50 e 46%, respectivamente, além de efeito na V%, sendo 24% superior ao controle; e na safra 2022/2023, o tratamento com maior destaque foi o uso de biochar, ocasionando efeito significativo na CTC a pH 7.0, com um incremento de 20% em relação ao controle. Na área familiar 2021/2022, K, P e rem-P, responderam com incrementos de 69%, 45% e 20%, respectivamente, em relação ao padrão. Nos indicadores biológicos para as respostas na área empresarial 2021/2022, a aplicação de COMBI apresentou diferenças significativas na CBM e atividade da Urease, verificando incrementos de 8% e 21% em comparação ao uso de fertilizante convencional, respectivamente. A produtividade diferiu estatisticamente, apenas em uma área e para a primeira safra de acordo com os tratamentos utilizados. A gestão de resíduos orgânicos na produção de condicionadores de solo se mostrou promissora, apresentando respostas nas relações de fertilidade e biologia do solo.

Palavras-chave: sequestro de carbono; efeito estufa; qualidade do solo; saúde do solo; *Coffea arabica*.

GENERAL SUMMARY

The increase in population necessitates higher agricultural production, which in turn produces considerable amounts of organic residue, including agricultural residues. A significant portion of agricultural residues originates from harvest and post-harvest processes. In Brazil, the coffee production chain plays a significant national and global economic role but also generates underutilized residues. In the context of a circular economy, transforming these organic residues can enable their reuse within agriculture. Composting, anaerobic fermentation, and pyrolysis are techniques that can be applied to manage coffee production residues. The application of products derived from these processes, known as soil conditioners, can enhance the effectiveness of conventional fertilizers and improve soil health compared to conventional management systems. The objective of this study is to compare the soil conditioning effects of coffee husk, organic compost, Bokashi, biochar, and COMBI (compost + biochar) on coffee cultivation in two coffee-producing areas (commercial and family farms) in the municipality of Santo Antônio do Amparo, MG, over two production seasons, 2021/2022 and 2022/2023. Biochar was produced through the pyrolysis of coffee husk and wood, while compost and Bokashi were primarily obtained from coffee husk as the main residue. These materials were chemically characterized. The treatments evaluated were: 1) raw coffee husk, 2) organic compost, 3) Bokashi, 4) biochar (coffee husk and wood), 5) COMBI, 6) commercial organomineral fertilizer, 7) conventional fertilization. Application rates of 5 or 10 tons per hectare of soil conditioners were used. Treatments 1 to 5 received conventional mineral fertilizer as a nutrient supplement. The experiment was conducted using a randomized block design with four replicates. Soil analyses, foliar analyses, evaluation of soil bioindicators, and analysis of coffee productivity were conducted. For the chemical attributes, significant differences were observed compared to the control in Area commercial during the 2021/2022 season for calcium and magnesium under the use of COMBI, with concentrations 50% and 46% higher, respectively. Additionally, an effect on base saturation (V%) was noted, with a 24% increase compared to the control. In the 2022/2023 season, the treatment with the most notable results was biochar, which significantly impacted CEC at pH 7.0, showing a 20% increase compared to the control. In Area family farms during the 2021/2022 season, K, P, and remaining P showed increments of 69%, 45%, and 20%, respectively, compared to the standard. For biological indicators in Area commercial during the 2021/2022 season, the application of COMBI resulted in significant differences in MBC and urease activity, with increases of 8% and 21%, respectively, compared to the use of conventional fertilizer. Productivity statistically differed in only one area and for the first harvest according to the treatments used. The management of organic residue in the production of soil conditioners has shown promise, presenting positive effects on the relationships between soil fertility and biology.

Keywords: carbon sequestration; greenhouse effect; soil quality; soil health; *Coffea Arabica*

INDICADORES DE IMPACTOS SOCIAIS, TECNOLÓGICOS E CULTURAIS DA PESQUISA

O trabalho de pesquisa intitulado **“Manejo de resíduos orgânicos na cadeia produtiva do café e seu impacto nos atributos do solo para promoção da economia circular”** apresenta relevantes impactos tecnológicos, econômicos e ambientais, ao explorar o uso potencial de alternativas para o adequado manejo dos resíduos da cafeicultura e sua interação com solos dentro de um conceito de circularidade. Por meio da agregação de valor aos resíduos da cafeicultura, utilizando processos que transformam essa matéria-prima em produtos capazes de auxiliar no desenvolvimento das plantas, o estudo difunde ferramentas importantes para o manejo sustentável de lavouras de café. O uso de condicionadores de solo, como composto orgânico, Bokashi e biochar, promove mudanças positivas na dinâmica química e biológica dos solos tropicais, contribuindo para a manutenção da saúde e qualidade do solo. Os processos de decomposição biológica e térmica envolvidos na produção desses condicionadores resultam em produtos mais estáveis, com maior concentração de nutrientes e na criação de habitats adequados para os microrganismos desempenharem suas funções essenciais no solo. Além disso, a aplicação desses condicionadores de solo proporciona um ambiente mais favorável para o desenvolvimento das culturas, podendo reduzir a dependência de insumos externos. As estratégias aplicadas neste trabalho estão alinhadas com os Objetivos de Desenvolvimento Sustentável (ODS), em especial os objetivos Fome Zero e Agricultura Sustentável (2), Consumo e Produção Responsáveis (12), Ação Contra a Mudança Global do Clima (13) e Vida Terrestre (15). Essas iniciativas contribuem para uma agricultura mais sustentável, com menores impactos ao meio ambiente e um grande potencial produtivo. A avaliação sistemática realizada neste estudo visa beneficiar tanto pequenos quanto grandes agricultores, além de fornecer embasamento técnico-científico para consultores, estudantes e pesquisadores. O trabalho busca elucidar questões relacionadas às tecnologias abordadas no nível de campo, promovendo sua aplicabilidade prática. Ademais, o estudo permitiu atingir, de forma abrangente, públicos externos à Universidade Federal de Lavras, fortalecendo o compromisso com parceiros do setor agrícola e consolidando seu papel na disseminação de conhecimento técnico e científico.

INDICATORS OF SOCIAL, TECHNOLOGICAL, AND CULTURAL IMPACTS OF THE RESEARCH

The research project entitled **“Management of Organic Waste in the Coffee Production Chain and Its Impact on Soil Attributes to Promote Circular Economy”** presents significant technological, economic, and environmental impacts by exploring potential alternatives for the

proper management of coffee farming waste and its interaction with soils within a circularity framework. By adding value to coffee farming residues through processes that transform this raw material into products capable of supporting plant development, the study disseminates essential tools for the sustainable management of coffee crops. The use of soil conditioners such as organic compost, Bokashi, and biochar fosters positive changes in the chemical and biological dynamics of tropical soils, contributing to the maintenance of soil health and quality. The biological and thermal decomposition processes involved in the production of these conditioners yield more stable products with higher nutrient concentrations and create suitable habitats for microorganisms to perform their essential soil functions. Additionally, applying these soil conditioners provides a more favorable environment for crop development, potentially reducing reliance on external inputs. The strategies employed in this research align with the United Nations Sustainable Development Goals (SDGs), particularly Zero Hunger and Sustainable Agriculture (Goal 2), Responsible Consumption and Production (Goal 12), Climate Action (Goal 13), and Life on Land (Goal 15). These initiatives promote more sustainable agriculture practices, with lower environmental impacts and significant productive potential. The systematic evaluation conducted in this study aims to benefit both small- and large-scale farmers, while also providing technical and scientific support to consultants, students, and researchers. The research seeks to elucidate field-level technologies, fostering their practical applicability. Furthermore, the study has effectively reached audiences beyond the Federal University of Lavras, reinforcing its commitment to agricultural sector partners and consolidating its role in disseminating technical and scientific knowledge.

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GENERAL INTRODUCTION

The global population has experienced rapid growth, increasing from 3.7 billion in 1970 to an estimated 7.9 billion in 2021, with projections of 9 to 11 billion by 2050 and 2100, respectively (Koop; Van Leeuwen, 2017). This continuous population growth raises concerns regarding solid residue production, a large portion of which is composed of organic residue (Chen et al., 2020). Proper residue management is essential to prevent the depletion of natural resources, reduce risks to human health, minimize potential environmental pollutants, and maintain global ecosystem balance.

Among these types of organic solid residue are sewage sludge, urban waste, food waste, kitchen waste, and animal and agricultural residue (Ashokkumar et al., 2022). Agricultural residues, particularly those resulting from harvest, can cause problems if indiscriminately dumped or burned (Babu et al., 2022). The growing population and economy in countries such as China, India, and Africa result in relative increases in agricultural residue, including seed pods, straws, husks, and animal manure (Koul et al., 2022; Wang et al., 2018). One of the productive chains that generates a high amount of residue is coffee production, and Brazil is the largest producer and exporter, with an estimated production of 55.1 million bags for 2023 and a record harvest of 61.6 million bags in 2020 (CONAB, 2024; MAPA, 2020). Consequently, there is a significant generation of direct and indirect residue, from rural properties to the final consumer. Globally, the coffee industry generates over 10 million tons of solid and liquid residue (Echeverria; Nuti, 2017).

In coffee processing, around 50% of the whole fruit's weight is residued, producing large amounts of coffee husk as a by-product. Other by-products from coffee processing include pulp, defective and immature beans, silver skin from roasting, and spent coffee grounds. For every ton of fresh coffee produced at the cherry stage, 12 to 50% of coffee husk can be generated (Oliveira; Franca, 2014; Hoseini et al., 2021). In addition to residues from coffee processing, pruning and coffee wood from the renewal of plantations also generate significant amounts of organic residues in coffee fields. However, these residues are often underutilized, typically burned as an energy source in drying machines or shredded and applied back to the fields. In one hectare of arabica coffee produced in Brazil, considering the national average of 26 bags per hectare, approximately 702 kg of coffee husk are generated per hectare. This is based on the fact that for every 100 kg of fresh cherry coffee, around 45 kg of coffee husk are produced, which represents about 45% of the total weight (CONAB, 2024; Oliveira et al., 2021). Given

this reality, it is necessary to seek alternatives for the proper use of these agricultural residues to achieve more sustainable coffee production.

Coffee production often follows an economy based on production, use, and subsequent disposal of by-products. However, to optimize the agricultural residues generated in this chain, the approach used by the circular economy, which consists of an economic system responsible for maximizing resource use and avoiding the disposable concept through reduction, reuse, recycling, and recovery of these residues in production, distribution, and consumption processes, can add value and create a sustainable perspective. (Luttenberg, *et al.*, 2020; Kirchherr *et al.*, 2017). Adopting this circular approach can reduce greenhouse gas emissions by up to 70% per nation, promoting a low-carbon economy (Stahel, 2016).

The circular economy creates a regenerative cycle, adding value and environmental responsibility to generated products. Applying this approach of reusing by-products within the coffee industry is necessary; however, the agricultural use of these residues without processing techniques can cause environmental issues. Coffee husks, for instance, need to be applied in large quantities to meet crop demands and, if not in optimal condition for returning to the field, can lead to soil and water pollution (Ijanu *et al.*, 2020). Techniques like composting, fermentation, and pyrolysis can create more stable and pollutant-free products, as harmful chemicals and bacteria are reduced during these processes due to the action of microorganisms and the heat generated during the decomposition of the initial biomass. (Waqas *et al.*, 2023).

Composting agricultural residue is the biological decomposition process under aerobic conditions (presence of oxygen), with moisture levels between 50 to 60% and temperatures ranging from 45 to 70 °C throughout the thermophilic phase causing a decomposition process. This process involves complex metabolic activities by different microbial communities that, in the presence of oxygen, consume the available nitrogen and carbon in the biomass (Azim *et al.*, 2018). At the end of this process, microbial degradation produces heat and a solid substrate with reduced carbon and nitrogen content, but with greater stability and higher concentrations of plant-available nutrients compared to the initial biomass condition (Roman *et al.*, 2015).

Pyrolysis of a given raw material at varying temperatures, typically between 350-750°C, produces biochar. This product has characteristics such as reduced biomass volume, concentrated mineral nutrients, and high carbon stability (intensified carbon sequestration), preventing its return to the atmosphere as CO₂ (Tan *et al.*, 2017; Joseph *et al.*, 2021). Additionally, biochar can improve the chemical, physical, and biological conditions of the soil due to its properties and reactions in the short, medium, and long term after application. Coffee husk biochar has excellent soil-use properties, such as high potassium (K) content, high carbon

content, and high cation exchange capacity (if produced at temperatures below 450°C). When applied to soil, it increases soil cation exchange capacity, whereas wood biochar mainly increases soil carbon content (Domingues et al., 2017; Domingues et al., 2020).

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SEGUNDA PARTE

ARTIGO

**Management of organic residues in the coffee production chain and their impact
on soil attributes for the promotion of circular economy**

ABSTRACT

The increase in the generation of agricultural, industrial, and domestic solid residue is a global issue that significantly contributes to environmental pollution. The coffee industry produces substantial volumes of residue which, if not properly managed, can lead to serious environmental impacts. Transitioning to a circular economy is crucial for developing sustainable solutions that make coffee production cleaner, maximizing the reuse, recycling, and recovery of resources throughout the production cycle. Methods such as composting, Bokashi use, and pyrolysis of biomass (biochar production) exemplify how these residues can be valorized to enhance soil fertility and reduce environmental pollution. The objective of this study was to compare the conditioning effects of products derived from different processes of transforming organic residue from the coffee industry on soil fertility and health. The experiment was conducted on two properties in Santo Antônio do Amparo, Minas Gerais, during the 2021/2022 and 2022/2023 agricultural years. Experimental area 1, located on a 2,000-hectare property with fully mechanized management, utilized the Acaia variety. Experimental area 2, situated on a 30-hectare property with semi-mechanized management, used the Mundo Novo variety. The evaluated treatments were coffee husk, organic compost, Bokashi, biochar (from coffee husk and wood), COMBI (compost + biochar), organomineral, and conventional fertilizer. The experiment was conducted in a randomized block design with four replications. Soil chemical analyses, biological soil indicators, and assessments of income and coffee productivity were performed. For the chemical attributes, significant differences were observed compared to the control in Area 1 during the 2021/2022 season for calcium and magnesium under the use of COMBI, with concentrations 50% and 46% higher, respectively. Additionally, an effect on base saturation (V%) was noted, with a 24% increase compared to the control. In the 2022/2023 season, the treatment with the most notable results was biochar, which significantly impacted CEC at pH 7.0, showing a 20% increase compared to the control. In Area 2 during the 2021/2022 season, K, P, and remaining P showed increments of 69%, 45%, and 20%, respectively, compared to the standard. For biological indicators in Area 1 during the 2021/2022 season, the application of COMBI resulted in significant differences in microbial biomass carbon (MBC) and urease activity, with increases of 8% and 21%, respectively, compared to the use of conventional fertilizer. The principal component analysis it possible to visualize the main variables responsible for determining the treatments. Given these results, the transformation of coffee growing biomass into soil conditioners presents a promising perspective for the management of organic residue from this production chain.

Keywords: carbon; greenhouse effect; soil quality; soil health; biological indicators, *Coffea arabica*.

1. INTRODUCTION

The increasing generation of solid residue, including agricultural, industrial, domestic, human, and animal residue, poses a significant problem, contributing to environmental pollution worldwide (Capanoglu *et al.*, 2022). The coffee industry is responsible for producing large volumes of solid residue, which can lead to serious environmental issues if not properly handled. It is estimated that around 10 million tons of solid and liquid residues are generated in coffee farming globally (Echeverria; Nuti, 2017). Therefore, adopting a circular economy approach is essential for developing sustainable solutions to make coffee production cleaner (Van Keulen; Kirchherr, 2021).

In a circular economy approach, resources are maximized through reuse, recycling, and recovery, aiming to create a closed-loop system where residue is minimized, and resources are continuously cycled back into the economy, thus integrating the entire production cycle (Luttenberg, 2020). However, currently coffee cultivation usually follows a linear economy model, where resources are used to produce goods, but residues are discarded without further treatments (Mayson; Williams, 2021), potentially leading to soil and water pollution (Ijanu *et al.*, 2020). While disposing of agricultural residue in the field can improve soil fertility, it also produces greenhouse gases (GHG) such as CO₂ (carbon dioxide), CH₄ (methane), and N₂O (nitrous oxide). Untreated disposal of this residue can contribute for up to 21% of GHG emissions in agriculture, alongside with other residue management methods (Mengqi *et al.*, 2021; FAO, 2016). Thus, transitioning to a circular economy could help mitigate these environmental impacts by ensuring that residue is managed more sustainably.

Within the circular economy, residue is transformed into valuable byproducts, creating a regenerative cycle. For instance, coffee husks, coffee residue water, and coffee pruning residues can be converted through composting, recycling nutrients back into the soil and reduces the need for chemical fertilizers (Hoseini *et al.*, 2021). Composting is a biological process that decomposes organic matter into a nutrient rich soil amendment, enhancing soil structure, water retention, and microbial activity (Azim *et al.*, 2018; Sanchez *et al.*, 2017). Continuous use of compost in coffee plantations has been shown to increase soil fertility slightly above the recommended levels for coffee, particularly in terms of P and soil pH. The combined application of compost and green manure has been found to balance soil fertility more effectively (Martins Neto *et al.*, 2020). However, new studies comparing the conditioning effects of various organic amendments on soil health to optimize soil fertility and sustainability in coffee production are still lacking.

Bokashi is another organic residue treatment process that can be used as an alternative for the reuse of coffee by-products. Bokashi production involves an anaerobic decomposition process, where organic materials are inoculated with anaerobic microorganisms, promoting faster degradation of the organic materials. Compared to organic compost, one key difference is that Bokashi retains more organic carbon, enabling its sequestration into the soil. This higher carbon ratio ultimately stimulates microbial activity in the soil, which can be particularly beneficial in areas with poor soil quality, creating a healthier growing environment for crops (Olle, 2020). Additionally, using coffee husks in the production of fermented compost has been shown to increase potassium and calcium levels as the proportion of this residue was increased (Pian *et al.*, 2023). Thus, these combined benefits make Bokashi a valuable method for recycling coffee by-products.

Another promising approach to handling solid coffee residues is their conversion into biochar, achieved through pyrolysis at temperatures typically ranging from 350-750 °C (Joseph *et al.*, 2021). Pyrolysis is a thermochemical process that occurs in the absence of oxygen, breaking down organic materials into biochar, bio-oil and syngas. This method not only reduces the volume of the material, which is particularly beneficial for light materials such as coffee husk, but also concentrates mineral nutrients and stabilize the C fraction, enhancing its long-term persistence in the soil (Tan *et al.*, 2017). Coffee husk biochar is especially valuable as a soil amendment due to its high potassium content and high cation exchange capacity when freshly applied to soil (Domingues *et al.*, 2020; Lago *et al.*, 2021).

In general, organic compost, Bokashi, and biochar are characterized as soil conditioners. Their compositions improve the chemical, physical, and biological properties of the soil, aiding plant development by making nutrients more available in the soil (Karamina & Fikrinda, 2020). Thus, while biochar excels in carbon persistence in soil, Bokashi can offer immediate microbial benefits, and compost can provide a balanced nutrient profile. Comparing the effects of biochar, Bokashi, and compost in coffee production is essential for understanding how each method influences nutrient dynamics, soil health and crop productivity. Understanding these variations can help optimize practices to valorize organic residues and to enhance sustainable coffee cultivation.

Another effective strategy involves combining compost and biochar, which has been shown to have a synergistic effect that can positively impact crop productivity and quality (Wang *et al.*, 2019). This combination can be achieved either through co-composting or by simply mixing the two materials after they are prepared (Antonangelo *et al.*, 2021). Using compost and biochar, whether separately or mixed, affects soil microbial activity and,

consequently, soil health (Wang *et al.*, 2019). Notably, soil biological indicators, such as specific key enzymes, have been found to offer more precise insights into soil health and productivity compared to traditional soil chemical analysis (Aragão *et al.*, 2020). Integrating these biological indicators into soil assessments can provide a deeper understanding of how the different soil organic amendments influence soil conditions and crop performance.

Biological activity in soils can be observed through enzymes and microbial biomass, in their interaction processes in the rhizosphere region of plants (Antonious *et al.*, 2020). Urease plays a fundamental role in the hydrolysis of NH_3 and CO_2 , and this enzyme is responsible for regulating the supply of nitrogen (N) to plants, being mainly derived from microorganisms and plants (Mobley; Hausinger, 1989). In the conversion of organic phosphate esters into orthophosphate ions, which become available to plants, we have the activity of phosphatase (Araujo; Vihko, 2013). Phosphatase is produced by microorganisms in response to low levels of inorganic phosphate. Another enzyme involved in soil metabolic processes is β -Glucosidase, which plays a key role in the decomposition of soil organic matter and plant residues. This enzyme is sensitive to changes in management and organic or total carbon, and its activity is related to the breakdown of these organic compounds, making nutrients available for subsequent crops (Stott *et al.*, 2010).

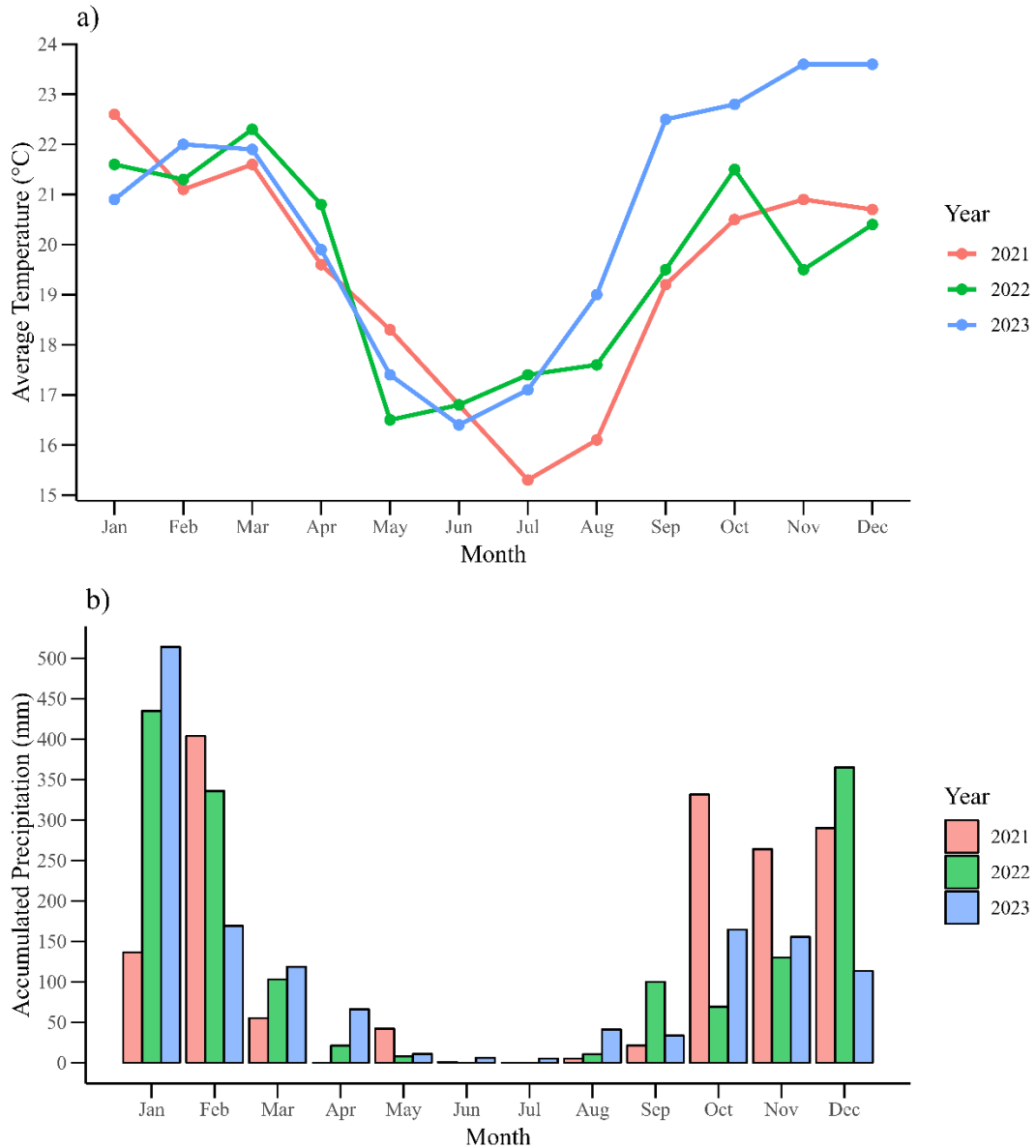
However, the comparison of such organic materials, including compost, biochar and Bokashi, specially under field conditions, are still limited. Therefore, this study aimed to evaluate the effects of different transformation processes of coffee cultivation organic residue on soil fertility and health, addressing this gap in the current literature.

2. MATERIAL AND METHODS

2.1. Characteristics of the experimental areas

The experiment was conducted on two farms in the municipality of Santo Antônio do Amparo, Minas Gerais, Brazil, during the agricultural years of 2021/2022 and 2022/2023. The sites were selected to represent diverse coffee farming conditions in the southern region of the state, characterized by varying soil fertility levels and different ages and varieties of coffee plants. One site is a smallholder coffee farm, while the other is a large-scale commercial operation, providing a contrast in coffee production management practices. Both areas are under rainfed conditions, with an altitude above 1000 m, average annual temperature of 19.8 °C, and precipitation of 1,670 mm. According to Köppen-Geiger classification, the region's climate is classified as Cwa (subtropical highland), characterized by a dry winter and hot summer. The climate data for the evaluated harvests can be observed in Figure 1S.

Figure 1S: Monthly average temperature (a) and accumulated precipitation (b) for the years 2021, 2022, and 2023, in different coffee plantations subjected to the use of soil conditioners produced from coffee farming residues.



Font: Autor (2024).

Experimental Area 1: Located at coordinates 20°54'58.1" S and 44°51'13.7" W, this site is part of a 2,000-hectare property where all farming operations, including soil preparation, fertilization, pesticide application, and harvesting, are mechanized. In the experimental area, the coffee variety used was Acaíá, planted at a spacing of 3.7 m x 0.6 m, with 7 years of establishment.

Experimental Area 2: Located at coordinates 20°52'39.2" S and 44°54'38.4" W, this site is a smallholder farm of 15 hectares dedicated to coffee cultivation. Farming practices are semi-mechanized, with most operations performed manually by the family group managing the

property. The coffee variety planted in the experimental area 2 is Mundo Novo, spaced at 3.5 m x 0.6 m, with 17 years of establishment.

The experiments were conducted using a randomized complete block design (RCBD), with four replications. Each plot contained 8 plants, with the central 6 plants considered as the useful area of the plot. The following treatments were evaluated: 1) coffee husk (CH), 2) organic compost (OC), 3) Bokashi (BK), 4) biochar (BC), 5) COMBI (compost + biochar, 1:1 w/w), 6) organomineral (OM), and 7) conventional fertilization (CF).

2.2. Fertilization management used in the experimental areas

In the first agricultural year, the application rate of each material (treatments 1 to 5) was 5 t ha⁻¹, in addition to the fertilizer (N, P, and K, from their respective sources) applied according to the recommendation of each farm, in a surface area. Fertilization was carried out in November in each evaluated harvest. For experimental area 1, fertilization included: 723 kg ha⁻¹ of agricultural gypsum; 197 kg ha⁻¹ of monoammonium phosphate (MAP); 612 kg ha⁻¹ of potassium chloride (KCl), split into two applications; and 518 kg ha⁻¹ of ammonium nitrate, split into three applications. In experimental area 2, the application included: 1,000 kg ha⁻¹ of dolomitic limestone and 857 kg ha⁻¹ of organomineral, composed of 12% nitrogen (N), 0.2% phosphorus pentoxide (P₂O₅), 12% potassium oxide (K₂O), and 9% organic carbon. All fertilizers and inorganic amendments were applied according to the local recommendations of each farm.

In the 2021/2022 harvest, the biochar treatment consisted solely of coffee wood biomass. And in the 2022/2023 harvest, this treatment was modified to include a mixture of coffee wood biochar and coffee husk (70%:30%). All treatments were reapplied in the second evaluated harvest. Furthermore, the application rates of organic materials (1 to 5) were increased to 10 t ha⁻¹ in experimental area 1, while remaining at the same rates as the previous year in experimental area 2. Phosphorus application was omitted in this harvest due to the high levels found in previous years (Table 2). The experimental plots received mineral fertilization with nitrogen (N) and potassium (K) to isolate the effect of soil conditioners. Nitrogen was applied using ammonium nitrate at rates of 340 and 260 kg ha⁻¹ in experimental areas 1 and 2, respectively. Potassium application was adjusted to match the levels present in the organic compost, which showed the highest total content of this element (Table 1), at rates of 326 and 163 kg ha⁻¹ of K in experimental areas 1 and 2, respectively. For plots with other soil

conditioners, K was applied using KCl, with both nutrients split into two applications. More details about the fertilization management can be found in Appendix 1.

2.3. Soil conditioners production and characterization

2.3.1. Compost preparation

The compost was prepared on a property (Experimental area 1 as described in 2.1) located in the municipality of Santo Antônio do Amparo, Minas Gerais (MG), Brazil. The raw materials were evenly distributed along a row in an open field for composting and included dry coffee husks (45% of the pile), wet-processed coffee pulp (35% of the pile), and cattle manure (20% of the pile). After distributing the organic materials, serpentine (a source of K 4,7%) and phosphate rock powder (a source of P 7,3%) were applied to achieve approximately 4.7% and 7.3% by mass in the composting pile, respectively. Residue water from coffee processing was added to reach the to reach 55 a 60% moisture level. The compost piles were mechanically turned, if necessary (when temperature exceeded 65 °C), based on daily monitoring to maintain the temperature between 55 and 65 °C during the thermophilic phase. After approximately 70 days, the compost was ready for field application.

2.3.2. Bokashi preparation

The production of Bokashi involved the addition of a solution made of water and biological yeast (*Saccharomyces cerevisiae*) with a concentration of 0.025%, along with sugar as a sucrose source, to a mixture of coffee husks (50% of the pile), cattle manure (45% of the pile), cornmeal (4% of the pile), and wood ash (1% of the pile). The solution was applied in layers using a watering can, and addition water was added to reach 55 a 60% moisture level, and the pile was manually turned. The pile was then covered with a tarp that had a white exterior and a black interior, ensuring good air sealing. When necessary ($T > 45$ °C), the pile was turned to keep the temperature below 45 °C during the thermophilic phase. After about 90 days, the Bokashi was ready.

2.3.3. Biochar preparation

The biochars used in the experiments were produced from coffee wood (including orthotropic branches and large roots) from a coffee plantation renewal about 3 years prior, which had been left exposed in the field, and coffee husks collected after grain processing. In the first experiment, only coffee wood biochar was used in both areas. In the second year, however, a mixture of these biochars was applied, consisting of 70% wood and 30% coffee

husks. Both types of biochar were produced at the Peixoto property, located approximately 12 km from the city of Santo Antônio do Amparo, MG, Brazil.

The wood was pyrolyzed in an earth pit kiln, as described by Cornelissen et al. (2016), with dimensions of 0.61 m (depth), 0.35 m (small base radius), and 0.65 m (large base radius) (Figure 2S). The wood was gradually fed into the kiln to maintain an anaerobic layer, with each batch requiring about 2 hours to complete. The process was concluded with rapid cooling using water, and the biochar was then air-dried. The coffee husk biochar was produced using a small-scale carbonizer (Figure 3S). The husks were placed at the base of the carbonizer for thermal treatment and heated internally to avoid air contact. The pyrolysis process was terminated with water, and the resulting biochar was air-dried. Subsequently, the air-dried wood biochar was ground, homogenized, and sieved through a 4 mm mesh screen to prepare it for field application. The coffee husk biochar, already in particulate form, was applied as produced

Figure 2S: Trench during and after the pyrolysis process to produce coffee wood biochar.



Font: Autor (2022).

Figure 3S: Biochar production process from coffee husks using implements for small productions.



Font: Autor (2022).

To characterize the products used in the experiment, composite samples of each material were collected and sieved through a 2 mm sieve for subsequent laboratory analysis. Biochar was characterized following the methods described by (Singh et al. (2017)). The parameters evaluated included moisture content, ash content, total carbon, pH, electrical conductivity, total and available nutrient contents, and cation exchange capacity (CEC) (Table 1). Organic compost, Bokashi, and organomineral fertilizer were analyzed according to the manual of official analytical methods for fertilizers and soil conditioners (MAPA, 2017). This included determination of moisture content at 65 °C, pH, electrical conductivity, total nitrogen content, total phosphorus content, organic carbon, CEC, and other macro and micronutrients using the nitric-perchloric acid digestion method (Table 2).

Table 1: Elementary chemical characteristics of soil conditioners used in the experimental coffee plantation area during the 2021/2022 and 2022/2023 agricultural years

Soil conditioners	Crop 2021/2022								
	pH	C.E	C	N	P	K	Ca	Mg	S
	-	$\mu\text{S}/\text{cm}$	%			g kg^{-1}			
Coffee wood biochar	9.8	600	68.1	-	0.6	6.5	13.4	3.1	0.1
Bokashi	7.7	-	20.7	18.1	4.6	20.7	25.9	9.9	2.0
Compost	7.9	-	40.6	12.5	4.5	18.2	39.6	13	3.0
Coffee husk	5.2	-	11.4	19.1	1.2	31.1	5.0	1.6	1.3
Organomineral	6.6	-	6.9	139	7.6	67.5	13.3	4.4	1.2

Crop 2022/2023									
Soil conditioners	pH	C.E	C	N	P	K	Ca	Mg	S
	-	$\mu\text{S/cm}$	%	g kg^{-1}					
Coffee husk biochar	10.3*	2310	55.8	-	2.5	22,1	8.2	2.2	1.2
Coffee wood biochar	9.9	586	82.7	-	1.8	3,0	9.3	2.1	0.4
Bokashi	8.4	-	24.9	30.0	4.6	21,8	10.8	5.7	4.6
Compost	8.1	-	13.0	16.3	10.7	26,9	51.9	21.3	39.8
Coffee husk	8.1	-	36.6	21.5	1.5	19,9	6.7	1.9	2.5
Organomineral	6.2	-	7.6	90.0	23.8	119	52.1	5.4	4.1

*: Mean value (n=3 analytical samples); EC: electrical conductivity; C: Total carbon; N: Nitrogen; P: Phosphorus; Ca: Calcium; Mg: Magnesium; S: Sulfur.

2.4. Evaluations conducted in the experimental coffee plantations

In both harvests, evaluations were conducted in the soil-plant system, focusing on crop productivity as well as soil quality and health, particularly soil fertility and microbiology. For soil chemical analyses, samples were taken from each experimental plot, with four samples collected from a depth of 0 to 20 cm to make a composite sample. Soil chemical attributes such as pH in water, organic matter, available levels of phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), sum of bases, effective cation exchange capacity (t), cation exchange capacity at pH 7.0 (T), base saturation (V%), and remaining P (rem-P) were evaluated following the Brazilian protocol (Teixeira, 2017). At the beginning of the experiment, a characterization of the control sample of the area was performed to establish reference values for these chemical attributes. (Table 2).

Table 2: Values found in the areas at the beginning of the experiment for the chemical and physical characteristics of the experimental area analyzed in the year 2021, in coffee plantations with 7 and 17 years of establishment, Area 1 and Area 2, respectively.

Area	pH H_2O	P mg dm^{-3}	K mg dm^{-3}	Na	Ca	Mg	Al $\text{cmol}_c \text{ dm}^{-3}$	H+Al	SB	t	T	V %	m
r.v	6,0	12	70	-	2,4	0,9	15	5,0	36	4,6	8,6	60	15
1	5.3	48.7	166	0.0	1.7	0.5	0	4.6	2.6	2.5	7.2	35.6	0
2	5.3	13.7	142	0.0	2.2	0.7	0.2	4	3.3	3.5	7.3	45.3	5.7
Area	MO g kg^{-1}	rem-P mg L^{-1}	B	Zn ²⁺	Cu	Fe	Mn	S	Clay	Silt	Sand	Classification	
r.v	4,0	-	0,6	1,5	1,2	30	8	20	dag kg^{-1}				
1	1.4	11.6	2.9	5.4	3.1	30.2	6	59	48	8	44	Clayey	
2	3.5	27.5	0.1	1.9	2.9	27.3	5.1	30.7	63	12	23	Clayey	

r.v: reference value (Ribeiro et al., 1999); pH – Active acidity; P and K (Mehlich⁻¹); Ca and Mg (KCL extraction); H+Al – Potential acidity; SB – Sum of bases; t – Effective cation exchange capacity ; T – Cation exchange capacity at pH 7.0; V – Base saturation; m – Aluminum saturation; OM – Organic matter; rem-P – remaining P.

Sampling for biological indicators followed a similar procedure to that for soil chemical attributes but were collected from a depth of 0 to 10 cm and kept refrigerated (4 °C) until the analysis. Biological soil analyses included indicators such as microbial biomass carbon (MBC) (Brookes et al., 1985; Vance et al., 1987), basal microbial respiration (BMR) (Alef, 1995), and enzyme activities: β -glucosidase (Dick et al., 1997), acid phosphatase (Dick et al., 1997), and urease (Tabatabai; Bremner, 1972). These analyses followed the recommendations of Aragão et al. (2020) for evaluating biological soil quality indicators in coffee cultivation areas. The MBC analysis was performed immediately after sample collection, BMR and urease within 15 days, β -glucosidase within 60 days, and phosphatase within a maximum period of 120 days. A control sample was also collected to establish reference biological characteristics for the area. (Table 3).

Table 3: Values found in the areas at the beginning of the experiment for the biological soil characteristics analyzed in the year 2021, in the experimental area with coffee plantations established for 7 and 17 years, in Areas 1 and 2, respectively.

Area	¹ MBC	² MBR	³ qCO ₂	⁴ β -glucosidase	⁴ A. phosphatase	⁵ Urease
1	294.8	193.3	0.64	17.2	1245	55
2	187.6	392.2	2.1	28.6	1374	47.6

¹: ($\mu\text{g.C g}^{-1}\text{soil}$); ²: ($\text{mg.C-CO}_2 \text{ kg}^{-1} \text{ soil day}^{-1}$); ³: ($\mu\text{g.C-CO}_2 \mu\text{g}^{-1} \text{ C-MBC day}^{-1}$); ⁴: ($\mu\text{g.p-nitrofenol.g}^{-1} \text{ dry soil.h}^{-1}$); ⁵: ($\mu\text{g.NH}_4\text{-N g dry soil}^{-1} \text{ h}^{-1}$); ⁶: Overall mean; DF: degrees of freedom; CV: coefficient of variation; *: Significant at the 5% level, by the F test ($p < 0.05$); ns: Not significant, by the F test ($p < 0.05$).

2.5. Data analysis

Experimental data were subjected to Shapiro-Wilk normality test, studentized Breusch-Pagan homogeneity test, and Durbin-Watson independence test. After meeting the assumptions of the linear model, analysis of variance (ANOVA) was performed using the F-test ($p < 0.05$). When significant, treatment effects were compared using Dunnett test ($p < 0.05$), with conventional fertilizer application used as the control treatment. Principal component analysis was performed for the chemical and biological attributes of the soil, using the "vegan" package version 2.6-2 (Oksanen *et al.*, 2013). All data analysis and statistical procedures were conducted using R software with RStudio interface, v.4.3.3 (R core team. R, 2024).

3. RESULTS AND DISCUSSION

3.1. Chemical attributes in the study Area 1

Significant changes were observed in various soil attributes (Table 4). For the 2021/2022 harvest, there was a notable increase in Ca, Mg, base saturation, organic matter, and remaining P (an indicator of P buffering in the soil). On the other hand, there was a significant reduction in pH, K, and potential acidity compared to the initial values of the area (Table 2). In the subsequent harvest (2023/2024), there was a significant increase in cation exchange capacity (CEC) at pH 7.0 and in remaining P. Additionally, potential acidity significantly decreased (Table 4).

Table 4: Summary of ANOVA for evaluation of soil conditioner use in 7-year-old coffee plantation on soil chemical attributes - Area 1.

		Crop 2021/2022											
	DF	pH	K	P	Ca	Mg	H+Al	SB	t	T	V	MO	rem-P
		(H ₂ O)	mg dm ⁻³				cmolc dm ⁻³				%	g kg ⁻¹	mg.L ⁻¹
Treatments	6	15.12*	109*	51.3ns	3.19*	1.59*	2.77*	4.82 ^{ns}	5.07 ^{ns}	7.56 ^{ns}	65.1*	2.29*	25.9*
CV %	-	4.85	23.3	47.8	17	21.6	10.7	26.6	20.4	13.34	4.89	11.9	7.21
		Crop 2022/2023											
Treatments	6	4.9 ^{ns}	189 ^{ns}	35,9 ^{ns}	3.07 ^{ns}	1,23 ^{ns}	3,54*	4,77 ^{ns}	4,92 ^{ns}	8,42*	57 ^{ns}	2,61 ^{ns}	26.9*
CV %	-	4.17	28,4	46,2	19.2	28.7	9,7	20,6	20,4	6,75	15,5	11	10.4

¹: Overall mean; DF: degrees of freedom; CV: coefficient of variation; *: Significant at the 5% level, by the F test ($p < 0.05$); ns: Not significant, by the F test ($p < 0.05$).

Concerning soil chemical attributes, when comparing the effects of soil conditioners to the control (conventional fertilization), only K (2021/2022 harvest) and remaining P (2022/2023 harvest) did not show significant differences. Soil pH, for instance, showed variations among treatments. Organic compost, Bokashi, biochar, and the COMBI treatments, resulted in increased soil pH, with respective increases of 0.78, 0.51, 0.51, and 0.58 compared to the control pH of 4.66 (Figure 1a).

These results align with existing research on the effects of organic amendments on soil. The mineral rich organic fractions of these amendments tend to have a buffering effect, which can moderate soil acidification and lead to less pronounced change in pH compared to conventional fertilizers (Wang *et al.*, 2019; Yang *et al.*, 2016). In contrast, nitrogenous fertilizers, particularly those containing ammonium nitrate, and urea, can lower soil pH by contributing H⁺ ions through the solubilization of these molecules, thereby increasing soil acidity (Pahalvi *et al.*, 2021; Rashmi *et al.*, 2020).

The COMBI conditioner showed a notable effect on Ca and Mg content compared to the control (conventional fertilization). Calcium content in the COMBI treatment was $5.2 \text{ cmol}_c \text{ dm}^{-3}$ and Mg content of $2.2 \text{ cmol}_c \text{ dm}^{-3}$, representing increases of $2.6 \text{ cmol}_c \text{ dm}^{-3}$ and $0.8 \text{ cmol}_c \text{ dm}^{-3}$, respectively, over the control, which had values of $2.6 \text{ cmol}_c \text{ dm}^{-3}$ for Ca (Figure 1b) and $1.4 \text{ cmol}_c \text{ dm}^{-3}$ for Mg (Figure 1c). Base saturation in the control treatment was 52.7%, significantly lower compared to coffee husk (+14%), organic compost (+17.3%), Bokashi (+13.3%), biochar (+10.2%), and COMBI (+24.3%) (Figure 1d). The response of the COMBI treatment for Ca, Mg, and base saturation is evident, showing a greater response compared to the control.

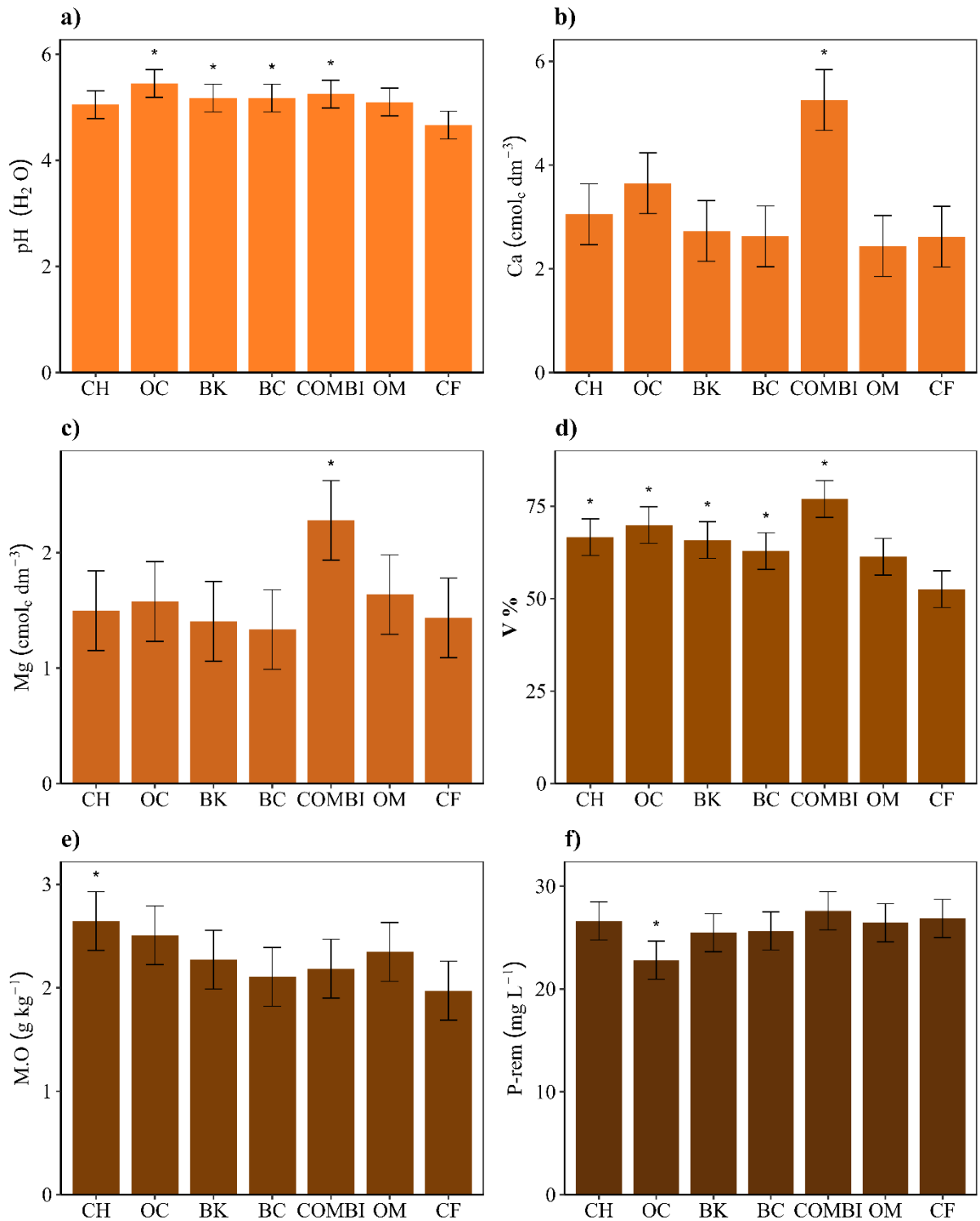
These increases can be attributed to the combined characteristics of the materials that constitute the COMBI treatment. On one hand, organic compost is rich in nutrients such as K, Ca, and Mg, which are crucial for soil fertility and plant growth. Biochar, on the other hand, has a high surface area and a negative surface charge that enhances its capacity to adsorb and retain these nutrients, reducing their leaching losses and making them more available to plants (Zhang *et al.*, 2016). Additionally, the slow-release properties of nutrients in biochar and compost mixtures provide a more sustained nutrient supply to plants, reducing the need for frequent fertilization.

Concerning soil organic matter content, significant differences were observed with the use of coffee husk as soil conditioner, showing an increase to 2.6 dag kg^{-1} ($+0.7 \text{ g kg}^{-1}$) compared to 1.9 dag kg^{-1} of organic matter in the control treatment (conventional fertilization) (Figure 1e). Biomasses applied directly to soils or after transformation processes such as the additives used in this study present accelerated decomposition when compared to more stable materials such as biochar. (Joseph *et al.*, 2021). Thus, such a significant increase in the short-term (2 years) was not expected from coffee husk application over other amendments. Further assessments in the longer-term might confirm whether this increase is consistent. Also, soil sampling under field conditions treated with organic amendments either incorporated or surface applied is always challenging to represent the real field variation (Lotz *et al.*, 2024).

Remaining P was lower with the application of the organic compost, showing a value of 22.8 mg L^{-1} compared to 26.8 mg L^{-1} in the control, resulting in a difference of -4.05 mg L^{-1} (Figure 1f). Remaining P refers to the portion of P that remains available in the soil after a certain period, following fertilization or natural processes. It is often used as an indicator of soil P buffering capacity and availability to plants. Organic matter in the soil can influence P adsorption because it competes with P for adsorption sites. This occurs because organic matter contains functional groups with negative charges that attract and retain P ions. However, the

effect of organic matter on remaining P can vary, and in some cases as increase in organic matter may lead to higher remaining P, as it can help keep P available by reducing its adsorption to soil minerals, particularly by blocking adsorption sites on Al and Fe oxides and hydroxides (Regelink *et al.*, 2015). Conversely, in other cases, organic matter may bind with P and compete for the same adsorption sites, which can reduce the amount of P available to plants and thus decrease the remaining P. Previous studies have confirmed that increased organic carbon from organic fertilizers can lead to a decrease in the availability of inorganic P (Frossard *et al.*, 1996; Shafqat; Pierzynski, 2013).

Figure 1: Assessment of pH (a), Ca (b), Mg (c), V% (d), M.O (e) and remaining P (f), in the use of air conditioners soil CH (Coffee husk), OC (Organic compost), BK (Bokashi), BC (Biochar), COMBI, OM (Organomineral) in relation to a control CF (Convectional fertilization) treatment, by Dunett test ($p < 0.05$), applied to a 7-year-old coffee crop planting in the 2021/2022 harvest – Area 1.



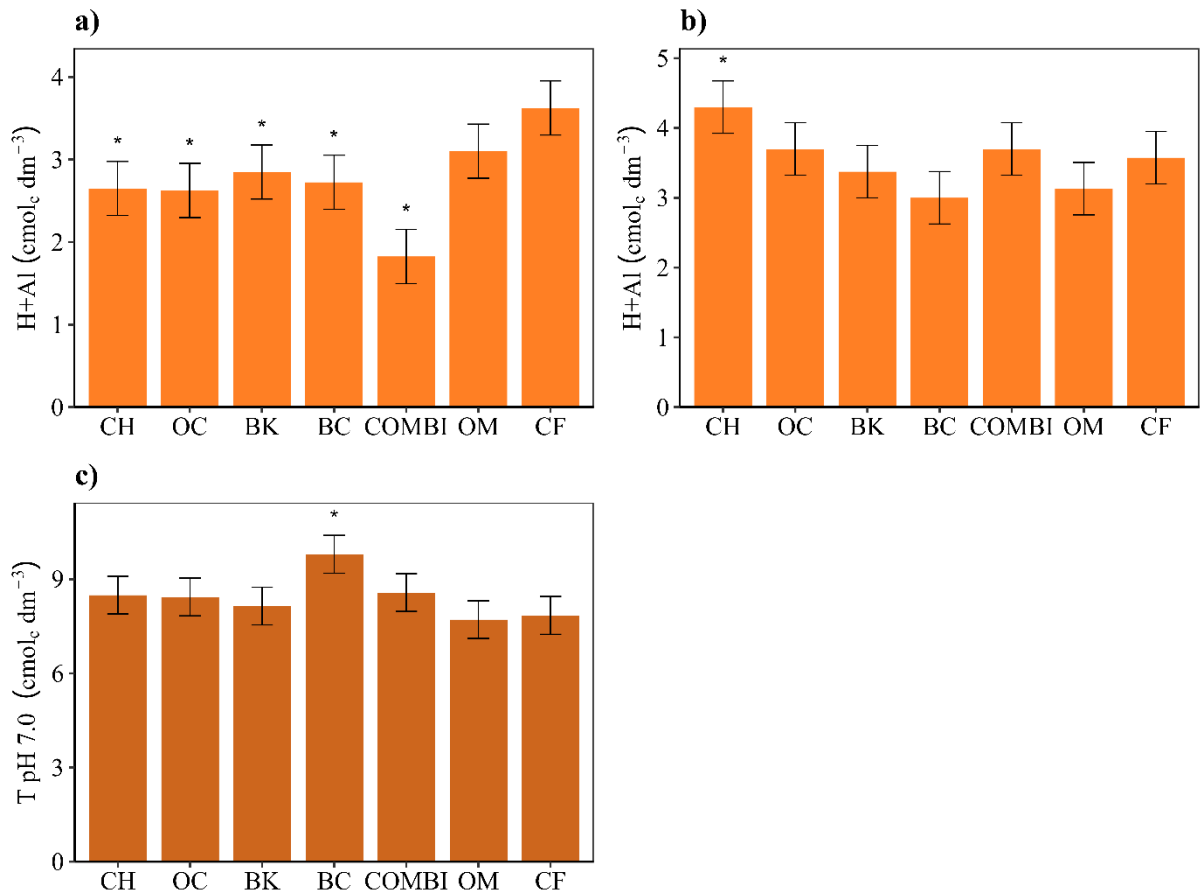
*Differential significance compared to the control treatment (FC), by Dunett test ($p < 0.05$); error bars referring to confidence intervals.

For potential acidity, all soil conditioners, except organomineral, showed estimated differences lower than the control in the 2021/2022 season. With conventional fertilizer, the potential acidity was 3.2 cmol_c dm⁻³, and significant reductions were observed with coffee

husk (-0.9 cmol_c dm⁻³), Bokashi (-0.7 cmol_c dm⁻³), biochar (-0.9 cmol_c dm⁻³), and COMBI (-1.8 cmol_c dm⁻³) (Figure 2a). In the 2022/2023 season, potential acidity showed an effect only with the application of coffee husk compared to the control treatment, resulting in an estimated difference of +0.7 cmol_c dm⁻³ of H+Al. In comparison to the 2021/2022 season (Figure 1g), coffee husk (CH) application showed a 38% increase in H+Al (Figure 2b). However, this trend of increased potential acidity was observed across all treatments except for the control. This indicates that the increase in potential acidity was a transient effect of the organic conditioners.

The cation exchange capacity for this season 2022/2023 indicated an estimated difference in biochar application, reaching 9.1 cmol_c dm⁻³ compared to 7.8 cmol_c dm⁻³ in the control, resulting in an estimated difference of 1.9 cmol_c dm⁻³ of T pH 7.0 (Figure 2c). Responses to the application of biochar derived from organic residues are usually observed in the form of higher organic matter content, nutrient availability, and high CEC (Lehmann; Joseph, 2024). This potential increase in CEC is due to the presence of organic functional groups; however, this characteristic of biochar is not solely responsible for changes in soil CEC, as it is also influenced by the application rate and the liming value of the material (Mia, *et al.*, 2017; Domingues *et al.*, 2017).

Figure 2: Evaluation of H+Al (2021/2022 and 2022/2023) (a and b) and T pH 7.0 (2022/2023) (c) with the use of soil conditioners CH (Coffee husk), OC (Organic compost), BK (Bokashi), BC (Biochar), COMBI, OM (Organomineral) compared to a control treatment CF (Conventional fertilization), by Dunnett test ($p < 0.05$), applied in a 7-year-old coffee plantation during - Area 1.



*Differential significance compared to the control treatment (FC), by Dunett test ($p < 0.05$) error bars referring to confidence intervals.

3.2. Chemical attributes in the study area 2

For the study area 2, there was a significant increase in pH, K, potential acidity, and organic matter, and a significant decrease in P and remaining P compared to the values found in the areas at the beginning of the experiment (Table 2) in the 2021/2022 crop season. In the subsequent 2022/2023 year, there was a significant increase in Mg, potential acidity, and CEC at pH 7.0. However, in the same season, there was a reduction in available P and base saturation (Table 5).

Table 5: Summary of ANOVA for evaluating the use of soil conditioners in a 17-year-old coffee plantation regarding soil chemical attributes - Area 2.

		Crop 2021/2022											
Treatments	DF	pH	K	P	Ca	Mg	H+Al	SB	t	T	V	MO	rem-P
		(H ₂ O)	mg dm ⁻³				cmol _c dm ⁻³				%	g kg ⁻¹	mg.L ⁻¹
	6	15.75*	344*	32.9*	3.46 ^{ns}	0.91 ^{ns}	4.24*	5.27 ^{ns}	5.59 ^{ns}	9.68 ^{ns}	55.7 ^{ns}	3.95*	19.4*
CV %	-	2.9	23.6	27.1	25.6	17.1	13.36	11.2	24.2	9.71	14.9	5.04	10.4
		Crop 2022/2023											
Treatments	6	5.02 ^{ns}	226 ^{ns}	8.08*	2.98 ^{ns}	0.88*	5.57*	4.39 ^{ns}	4.57 ^{ns}	10*	43.7*	4.2 ^{ns}	16.6 ^{ns}

CV %	-	6.11	39.7	41	25.9	22.8	20.3	25.5	24.4	6.82	21.8	12.1	15.9
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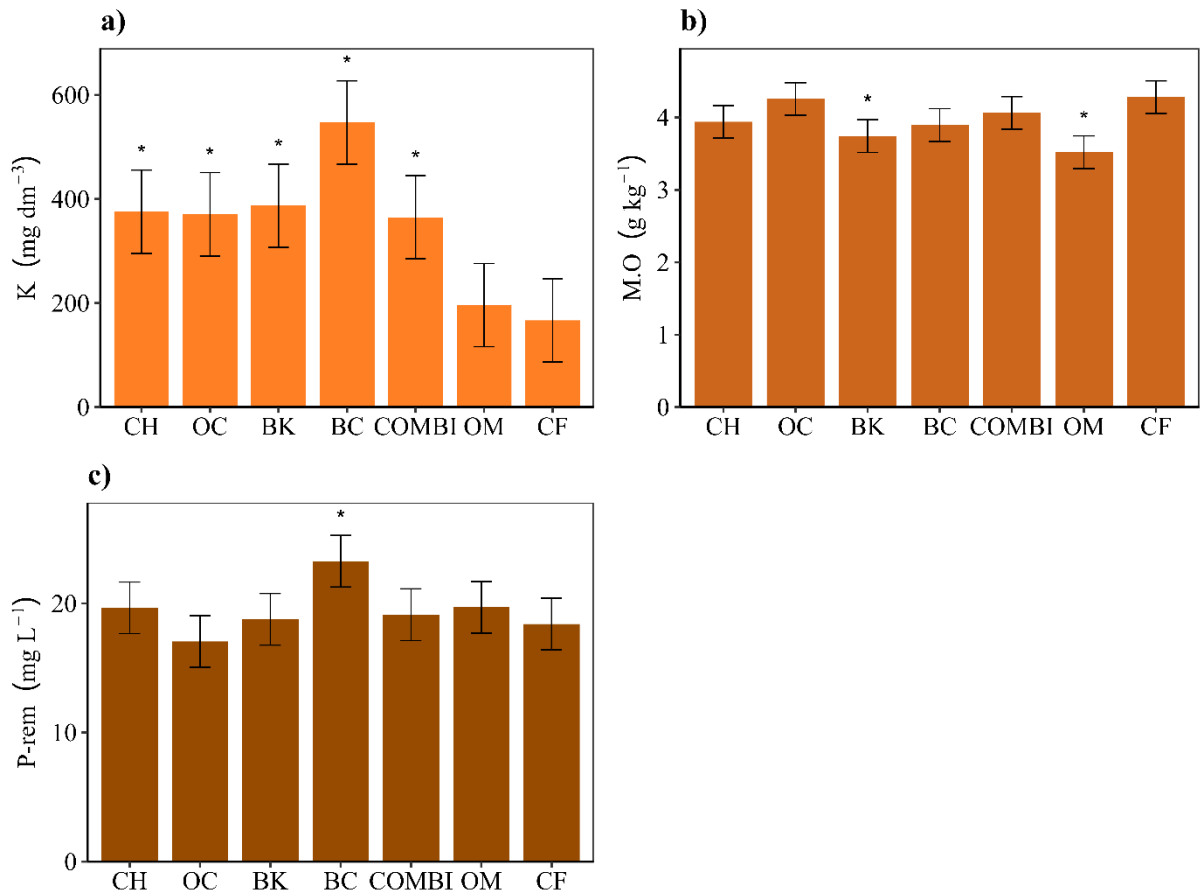
¹: Overall mean; DF: degrees of freedom; CV: coefficient of variation; *: Significant at the 5% level, by the F test (p < 0.05); ns: Not significant, by the F test (p < 0.05).

For available K, several treatments outperformed the control, which had 167 mg dm⁻³ of K. The treatments showing higher levels of available K were coffee husk (+208 mg dm⁻³), organic compost (+203 mg dm⁻³), Bokashi (+220 mg dm⁻³), biochar (+380 mg dm⁻³), and COMBI (+198 mg dm⁻³) (Figure 3a). These soil conditioners, when combined with KCL supplementation, resulted in increases of 55% (CH), 54.9% (OC), 56.8% (BK), 69.4% (BC), and 54.2% (COMBI) compared to conventional fertilizer. Coffee husk generally contain high amounts of soluble K, which can vary depending on their origin and the processing of the raw material. Potassium present in coffee husks or in organic compounds derived from coffee husks are highly soluble and can be rapidly released to soils (Oliveira; Franca, 2015; Zoca et al., 2014).

Regarding organic matter content, the response was lower for Bokashi and organomineral treatments compared to the control, with estimated reductions of 0.5 and 0.7 g kg⁻¹, respectively. The control had an average organic matter content of 4.2 g kg⁻¹ (Figure 3d). The remaining P increased to 23.2 mg L⁻¹ with biochar treatment as compared to 18.4 mg L⁻¹ in the control (Figure 3b).

The application of biochar can enhance the availability of P in soil, especially when combined with the application of phosphate fertilizers. Biochar has a low capacity to retain P due to its negative surface, but when associated with metals like calcium biochar can effectively increase P adsorption that can become available to plants afterwards (Zhang et al., 2016). Additionally, the difference in remaining P in the soil when organic matter or biochar is applied can be significant. Biochar interacts with P primarily through its surface chemistry, which differs from that of organic matter due to its unique physical and chemical properties. Biochar's surface contains various functional groups such as hydroxyl (-OH), carboxyl (-COOH), and phenolic groups. Compared to natural dissolved organic matter, biochar dissolved organic matter has many more reactive groups. This increased reactivity can lead to greater oxyanion competition and displacement of adsorbed P on soil minerals (Yang et al., 2021).

Figure 3: Evaluation of K (a), M.O (b) and remaining P (c) with the use of soil conditioners CH (Coffee husk), OC (Organic compost), BK (Bokashi), BC (Biochar), COMBI, OM (Organomineral) compared to a control treatment CF (Conventional fertilization), by Dunnett test (p<0.05), applied in a 17-year-old coffee plantation during the 2021/2022 crop season - Area 2.



*Differential significance compared to the control treatment (FC), by Dunett test ($p < 0.05$) error bars referring to confidence intervals.

The application of biochar showed a higher response for available P (49.3 mg dm^{-3} of P) (Figure 4a) compared with conventional fertilization (27 mg dm^{-3} of P), with an increase of 45% ($+22.3 \text{ mg dm}^{-3}$ of P). However, when compared to the values found in the areas at the beginning of the experiment (Table 2), this increase was of 72%. This is not only associated with the response of this soil conditioner but also with the phosphate fertilization management used in this first crop season.

The use of biochar can influence various processes involved in the dynamics of P in the soil, such as pH alteration, changes in the equilibrium of adsorption and desorption processes, and its impact on microbial enzyme activities, which result in changes in P solubility (Gao et al., 2017; Gao et al., 2016; Xu et al., 2014). These increases in available P in soils following biochar application have been observed in numerous studies, with such responses being detected within less than a year after application (Gao et al., 2019).

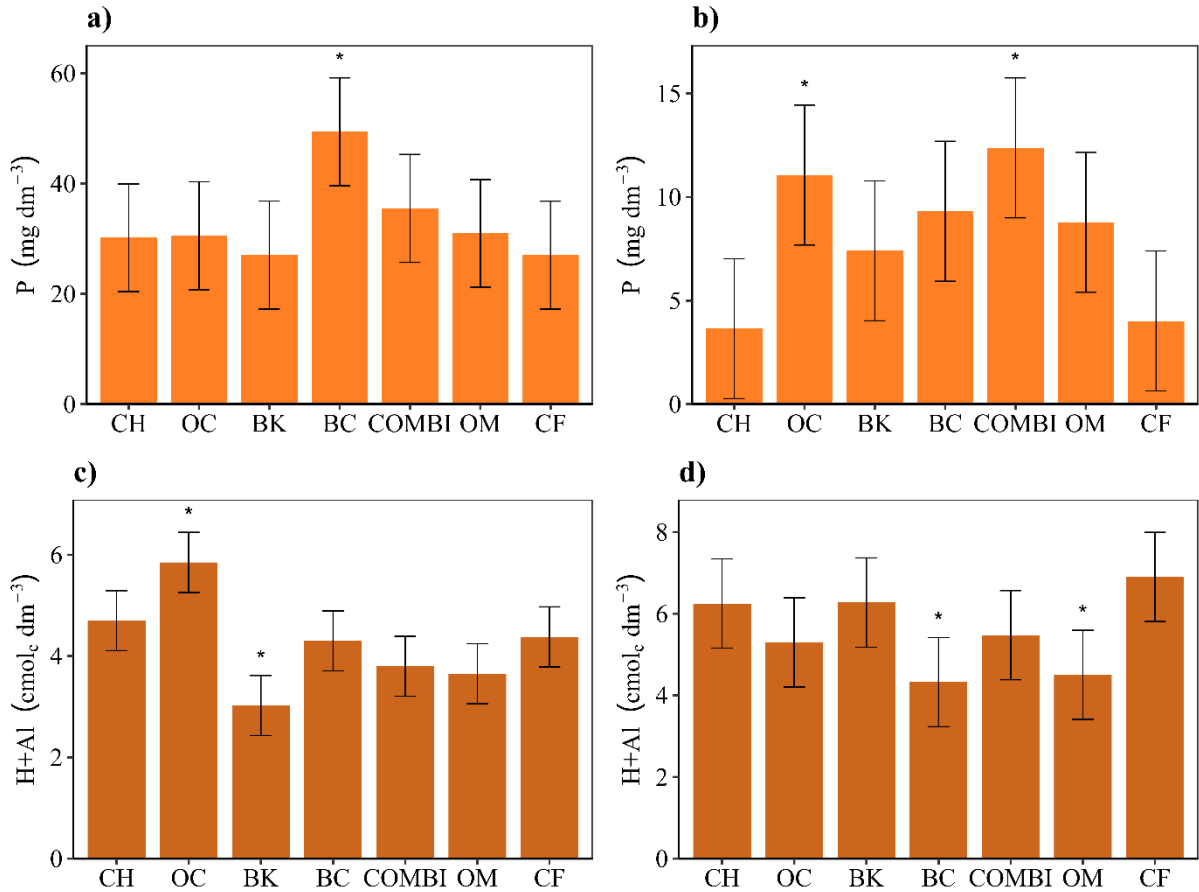
In the second crop season of this area, a sharp reduction of available P was observed, directly related to the absence of phosphate fertilization, considering the high levels found in

the previous year's evaluation. Despite the reduction, the levels of available P found in the treatments were still considered moderate to high for tropical soil characteristics. In terms of estimated differences, the treatments of OC (11 mg dm⁻³ of P) and COMBI (12.3 mg dm⁻³ of P) differed from the control (4 mg dm⁻³ of P) (Figure 4b). These increases were 63.6% and 67.4% higher compared to the control, respectively. However, these same soil conditioners showed reductions of 63.9% and 65.3% when compared to the 2021/2022 crop season (Figure 3a).

The use of organic compost in the field can progressively increase the availability of P when applied consistently in agriculture. In contrast, the available fraction of P is relatively lower in controls with mineral fertilization only. This is primarily due to the high application rates of organic compost, which can provide substantial amounts of P (Nobile et al., 2020). The biomass used in the production of organic compost-biochar (COMBI) directly influences its effects on P availability, as both components of this soil conditioner enhance its beneficial properties. The phosphate content varies across studies; however, the P reserves in the added biochar and the contribution of the compost are crucial factors (Antonangelo et al., 2021; Vandecasteele et al., 2016; Zhang et al., 2016).

Analyzing the response to potential acidity in area 2, it was found that two conditioners showed estimated differences compared to the control (4.7 cmol_c dm⁻³): organic compost increased potential acidity by 1.4 cmol_c dm⁻³, while Bokashi decreased it by 1.3 cmol_c dm⁻³ (Figure 4c). Regarding potential acidity, despite an overall increase in its concentration in the soil when comparing the 2021/2022 and 2022/2023 crop seasons, the use of biochar (4.3 cmol_c dm⁻³ of H+Al) and organomineral (4.5 cmol_c dm⁻³ of H+Al) showed a reduction compared to the control (6.9 cmol_c dm⁻³ of H+Al), with estimated differences of -2.5 cmol_c dm⁻³ and -2.4 cmol_c dm⁻³ of H+Al, respectively (Figure 4d).

Figure 4: Evaluation of P (2021/2022 and 2022/2023) (a and b), H+Al (2021/2022 and 2022/2023) (c and d) with the use of soil conditioners CH (Coffee husk), OC (Organic compost), BK (Bokashi), BC (Biochar), COMBI, OM (Organomineral) compared to a control treatment CF (Conventional fertilization), by Dunett test ($p < 0.05$), applied in a 17-year-old coffee plantation during - Area 2.



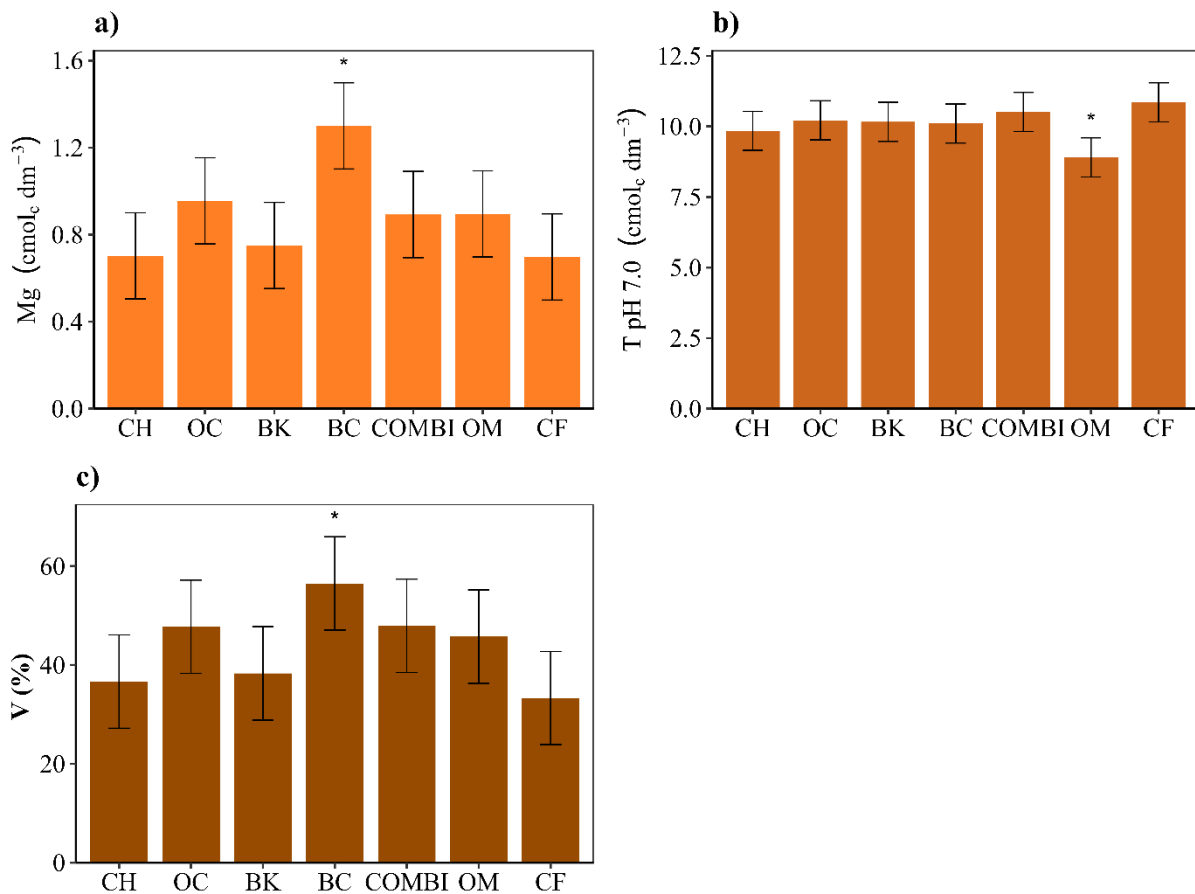
Unlike the first season, the second season showed a notable increase in exchangeable Mg levels with the use of biochar. The biochar treatment resulted in $1.3 \text{ cmol}_c \text{ dm}^{-3}$ of Mg (Figure 5a) compared to the control, which showed $0.6 \text{ cmol}_c \text{ dm}^{-3}$ of Mg, representing a 53.8% increase. When compared to the reference values found in the areas at the beginning of the experiment (Table 2), this increase was 46.1%. Coffee husk is rich in various macro and micronutrients, including Mg. Converting coffee husk into biochar concentrates the nutrient content of the biomass. Biochar produced at high temperatures tends to have higher concentration of exchangeable nutrients because these conditions eliminate low molecular weight acids and removes protons from the surface of its structure, leading to a greater increase of these elements in the soil (Whalen et al., 2024; Hoseni et al., 2021).

The potential cation exchange capacity also showed an effect in this second evaluation crop season. The only difference compared to the control was found in the application of

organomineral, which had $8.9 \text{ cmol}_c \text{ dm}^{-3}$ of T pH 7.0, which was $-1.95 \text{ cmol}_c \text{ dm}^{-3}$ lower than conventional fertilization ($10.8 \text{ cmol}_c \text{ dm}^{-3}$) (Figure 5b).

Another soil chemical attribute affected by the application of soil conditioners in this second crop season was base saturation. The use of Biochar (56.5%) differed from conventional fertilization (33.3%) by +23.1 V% (Figure 5c). This gain was consistent when compared to the values found in the areas at the beginning of the experiment (45.3%) (Table 2) and the 2021/2022 crop season, which showed a saturation of 51.2% for this soil conditioner.

Figure 5: Evaluation of Mg (e), T pH 7.0 (f), and V% (g) with the use of soil conditioners CH (Coffee husk), OC (Organic compost), BK (Bokashi), BC (Biochar), COMBI, OM (Organomineral) compared to a control treatment CF (Conventional fertilization), by Dunett test ($p < 0.05$), applied in a 17-year-old coffee plantation during the 2022/2023 crop season - Area 2.



*Differential significance compared to the control treatment (FC), by Dunett test ($p < 0.05$); error bars referring to confidence intervals.

3.3. Biological indicators of the study area 1

Regarding biological evaluations, a significant reduction was observed in the 2021/2022 season for microbial biomass carbon and urease enzymatic activity (Table 3). In contrast, there

was a significant increase in basal microbial respiration and soil metabolic quotient compared to the reference values found in the areas at the beginning of the experiment. Additionally, when compared with the background data of the biological indicators, a significant reduction effect was perceived for all analyzed variables in the second season, except for the soil metabolic quotient (Table 6).

Table 6: Summary of ANOVA for the evaluation of the use of soil conditioners in a 7-year-old coffee crop in Carbon from microbial biomass (MBC), Basal soil respiration (MBR), Metabolic quotient soil (qCO₂), β -glucosidase, Acid phosphatase, and Urease – Area 1.

Crop 2021/2022							
	DF	¹ MBC	² MBR	³ qCO ₂	⁴ β -glucosidase	⁴ A.phosphatase	⁵ Urease
Treatments	6	⁶ 212*	200*	1.27*	16 ^{ns}	1176 ^{ns}	61.3*
CV %	-	17	10.6	19.2	26.3	22.2	10.2
Crop 2022/2023							
	DF	¹ MBC	² MBR	³ qCO ₂	⁴ β -glucosidase	⁴ A.phosphatase	⁵ Urease
Treatments	6	289*	28.2*	0.11 ^{ns}	206*	643*	53.5*
CV %	-	21.6	22.9	67.4	15.6	14.3	28.7

¹: ($\mu\text{g C g}^{-1}\text{soil}$); ²: ($\text{mg C-CO}_2 \text{ kg}^{-1} \text{ soil day}^{-1}$); ³: ($\mu\text{g C-CO}_2 \mu\text{g}^{-1} \text{ C-MBC day}^{-1}$) ⁴: ($\mu\text{g p-nitrofenol.g}^{-1} \text{ dry soil.h}^{-1}$); ⁵: ($\mu\text{g NH}_4\text{-N g dry soil}^{-1} \text{ h}^{-1}$); ⁶: Overall mean; DF: degrees of freedom; CV: coefficient of variation; *: Significant at the 5% level, by the F test ($p < 0.05$); ns: Not significant, by the F test ($p < 0.05$).

Evaluating the 2021/2022 season, microbial biomass carbon (MBC) increased with the application of organic compost and COMBI, with estimates of 340 and 323 $\mu\text{g C g}^{-1} \text{ soil}$, respectively (Figure 6a). This increase corresponds to 13.2% and 8.7%, respectively, in relation to the reference values observed for CBM in area 1 (Table 3). In relation to conventional fertilization (159 $\mu\text{g C g}^{-1} \text{ soil}$), these values represent increases of 53.2% and 50.7% for organic compost and COMBI, respectively. Organic management systems generally exhibit higher levels of microbial biomass carbon (MBC) due to the addition of materials with a low carbon-to-nitrogen (C/N) ratio (e.g., organic compost), in comparison to more conventional cultivation practices (Lammel *et al.*, 2015; Ge *et al.*, 2013). The incorporation of biochar into compost creates habitats for microorganisms due to its porous surface and its capacity to adsorb organic matter and inorganic nutrients (Agegnehu *et al.*, 2017; Thies; Rillig, 2009). This characteristic likely influenced the increase in MBC observed with the use of COMBI. Another treatment that showed a difference from the control was organomineral fertilizer; however, there was a

reduction in MBC when compared to both the reference values of the area and the control treatment, being 78.9% and 61% lower, respectively.

In the 2022/2023 season, MBC showed a negative estimated difference compared to the control with the use of Bokashi and COMBI, with respective values of 214 and 202 $\mu\text{g C g}^{-1}$ soil, while the control had 356 $\mu\text{g C g}^{-1}$ soil for MBC (Figure 6b). A brief analysis between the two seasons reveals an increase in the control treatment for MBC (Figures 6a and 5b). However, comparing the use of Bokashi and COMBI in this same harvest, there is approximately one constancy for the application of Bokashi and a reduction in MBC values when COMBI was applied.

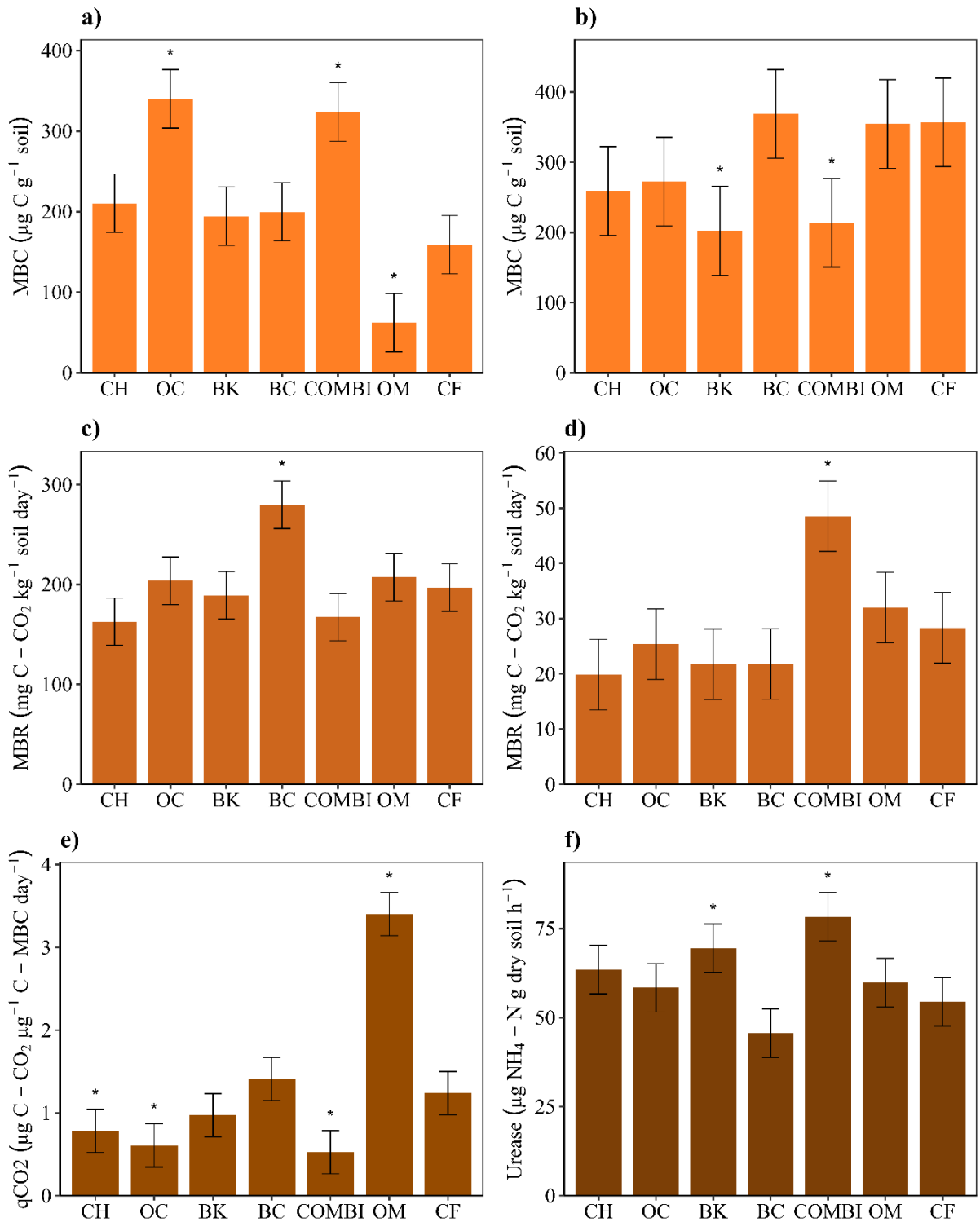
For basal microbial respiration (BMR), the only treatment that differed from the control was the application of biochar, with a BMR value of 279 $\text{mg.C-CO}_2 \text{ kg}^{-1} \text{ soil day}^{-1}$. This corresponds to an increase of 30.8% compared to the area's historical data (Table 3) and 29.7% compared to the use of conventional fertilization (Figure 6c). The higher basal microbial respiration (BMR) observed with the use of biochar is similarly reported in the literature and may be related to the increased availability of substrate, which consequently aids in the release of volatile materials and biologically active compounds. Additionally, the microenvironments provided by the biochar's pores are suitable for the microbial community (Karimi et al., 2020; Herrmann *et al.*, 2019). For BMR, there was an overall reduction in the area and COMBI was the only treatment that resulted in an estimated difference from the control (Figure 6d), with a value of 48.5 $\text{mg C-CO}_2 \text{ kg}^{-1} \text{ soil day}^{-1}$ compared to the control's 28.3 $\text{mg C-CO}_2 \text{ kg}^{-1} \text{ soil day}^{-1}$. However, in terms of magnitude, the reduction in BMR for COMBI was 71%, while for the control it was 85%. MBR is a biological attribute often used as a soil quality indicator; however, it can be altered based on changes in the microbial community due to the application of carbon sources or conditions that may be considered stressful to the environment (Aragão et al., 2020). The sharp reduction from the 2021/2022 to the 2022/2023 harvest could indicate a previous stress situation in the area. Although the $q\text{CO}_2$ was not significant, there was likely a lower activity in the 2022/2023 period due to the relationship between MBC and MBR, which might indicate a recovery from the stress condition.

In the BMR/MBC ratio ($q\text{CO}_2$), the treatments with estimated negative differences compared to the control were: coffee hush with -0.5 $\mu\text{g C-CO}_2 \mu\text{g}^{-1} \text{ C-MBC day}^{-1}$, organic compost with -0.6 $\mu\text{g C-CO}_2 \mu\text{g}^{-1} \text{ C-MBC day}^{-1}$, and COMBI with -0.6 $\mu\text{g C-CO}_2 \mu\text{g}^{-1} \text{ C-MBC day}^{-1}$. The control value for $q\text{CO}_2$ was 1.2 $\mu\text{g C-CO}_2 \mu\text{g}^{-1} \text{ C-MBC day}^{-1}$. In contrast, the use of organomineral showed a $q\text{CO}_2$ value of 3.6 $\mu\text{g C-CO}_2 \mu\text{g}^{-1} \text{ C-MBC day}^{-1}$ (Figure 6e),

representing increases of 83.3% and 66.5% compared to the area's reference values (Table 3) and the control, respectively.

Among the enzymatic activities, urease was the only enzyme that responded significantly to the treatments Bokashi and COMBI, with activities of 78.3 and 69.4 $\mu\text{g NH}_4\text{-N g dry soil}^{-1} \text{ h}^{-1}$). These values represent increases of 30% and 21% compared to the control (Figure 6f). The enzyme urease, which plays a role in the decomposition of organic residues, exhibits higher activity in areas with organic management, particularly with the application of coffee husk compost and castor bean cake (Lammel *et al.*, 2015).

Figure 6: Responses of biological indicators Microbial Biomass Carbon (2021/2022 and 2022/2023 (a and b), Basal Microbial Respiration (2021/2022 and 2022/2023) (c and d), Soil Metabolic Quotient (2021/2022) (e), and Urease Enzymatic Activity (2021/2022) (f) with the use of soil conditioners CH (Coffee husk), OC (Organic compost), BK (Bokashi), BC (Biochar), COMBI, OM (Organomineral) compared to a control treatment CF (Conventional fertilization), by Dunnett test ($p < 0.05$), applied in a 7-year-old coffee plantation during – Area 1.



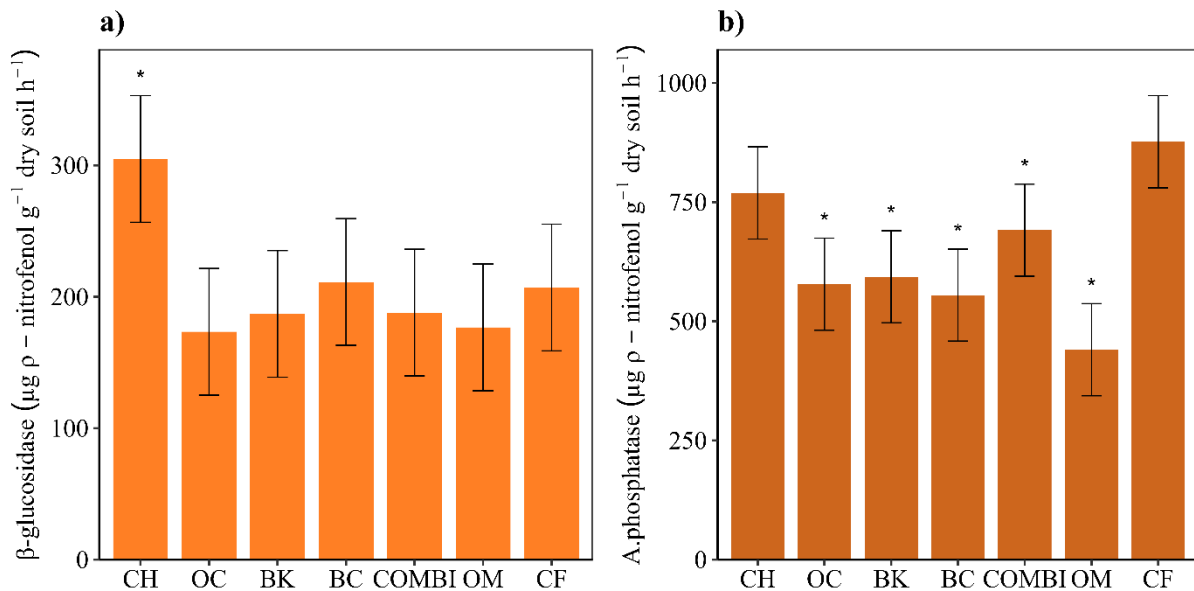
*Differential significance compared to the control treatment (FC), by Dunett test ($p < 0.05$); error bars referring to confidence intervals.

Regarding β -glucosidase enzyme activity, the coffee husk treatment resulted in a value of $304 \mu\text{g p-nitrophenol g}^{-1} \text{ dry soil h}^{-1}$, which differed from conventional fertilization, which

had a value of 207 $\mu\text{g p-nitrophenol g}^{-1}$ dry soil h^{-1} (Figure 7a). When compared to the area's reference value of 17.2 $\mu\text{g p-nitrophenol g}^{-1}$ dry soil h^{-1} , the coffee husk application showed a 94% increase in β -glucosidase over the evaluations.

For the acid phosphatase enzyme, a reduction in activity was noted across several treatments: organic compost (577 $\mu\text{g p-nitrophenol g}^{-1}$ dry soil h^{-1}), Bokashi (593 $\mu\text{g p-nitrophenol g}^{-1}$ dry soil h^{-1}), biochar (554 $\mu\text{g p-nitrophenol g}^{-1}$ dry soil h^{-1}), COMBI (691 $\mu\text{g p-nitrophenol g}^{-1}$ dry soil h^{-1}), and organomineral (440 $\mu\text{g p-nitrophenol g}^{-1}$ dry soil h^{-1}) (Figure 7b). The control treatment also showed a reduction in activity, with a value of 876 $\mu\text{g p-nitrophenol g}^{-1}$ dry soil h^{-1} , compared to the area's reference value of 1245 $\mu\text{g p-nitrophenol g}^{-1}$ dry soil h^{-1} . The use of mineral and organic fertilizers tends to result in lower values of acid phosphatase activity, similar to coffee plantations when compared to areas of secondary forest. This is possibly related to the capacity for the accumulation of organic matter and organic compounds (Pereira *et al.*, 2024; Evangelista *et al.*, 2012; Nunes *et al.*, 2009).

Figure 7: Responses of biological indicators β -glucosidase (a) and Acid Phosphatase Enzyme Activity (b) with the use of soil conditioners CH (Coffee husk), OC (Organic compost), BK (Bokashi), BC (Biochar), COMBI, OM (Organomineral) compared to a control treatment CF (Conventional fertilization), by Dunett test ($p < 0.05$), applied in a 7-year-old coffee plantation during the 2022/2023 crop season – Area 1.



*Differential significance compared to the control treatment (FC), by Dunett test ($p < 0.05$); error bars referring to confidence intervals.

3.4. Biological Indicators of the study area 2

Analyzing the responses of soil conditioners for area 2, a significant effect was observed in MBC, qCO_2 , and urease activity in the first evaluation season. However, there was a

reduction in MBC and urease, and an increase in qCO_2 compared to the reference values of the area (Table 3). In the following season, there were statistical difference in MBC and β -glucosidase, with both exceeding the control values reference for the area, while a reduction was noted for acid phosphatase (Table 7).

Table 7: Summary of ANOVA for the evaluation of the use of soil conditioners in a 17-year-old coffee crop in Carbon from microbial biomass (MBC), Basal soil respiration (MBR), Metabolic quotient soil (qCO_2), β -glucosidase, Acid phosphatase, and Urease – Area 2.

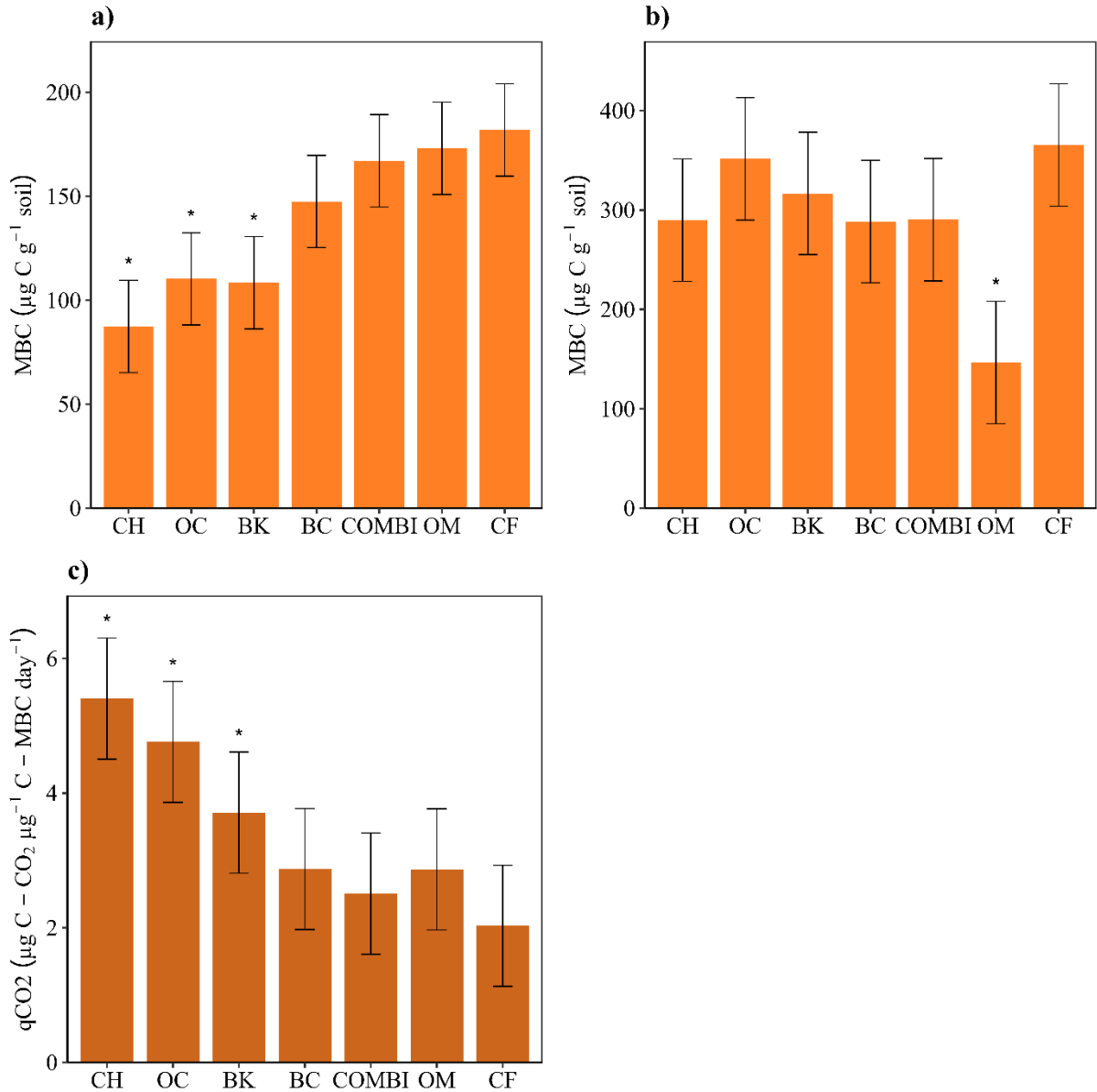
Crop 2021/2022							
Treatments	DF	¹ MBC	² MBR	³ qCO_2	⁴ β -glucosidase	⁴ A.phosphatase	⁵ Urease
	6	⁶ 139*	434 ^{ns}	3.4*	26.6 ^{ns}	1143 ^{ns}	35.3*
CV %	-	15.4	13.5	26.3	11.8	12.2	11.6
Crop 2022/2023							
Treatments	DF	¹ MBC	² MBR	³ qCO_2	⁴ β -glucosidase	⁴ A.phosphatase	⁵ Urease
	6	292*	30.6 ^{ns}	0.17 ^{ns}	125*	1010*	54.5 ^{ns}
CV %	-	18.3	39.4	68.7	11.5	9.08	38.3

¹: ($\mu\text{g C g}^{-1}\text{soil}$); ²: ($\text{mg C-CO}_2 \text{ kg}^{-1} \text{ soil day}^{-1}$); ³: ($\mu\text{g C-CO}_2 \mu\text{g}^{-1} \text{ C-MBC day}^{-1}$) ⁴: ($\mu\text{g } \rho\text{-nitrofenol.g}^{-1} \text{ dry soil.h}^{-1}$); ⁵: ($\mu\text{g NH}_4\text{-N g dry soil}^{-1} \text{ h}^{-1}$); ⁶: Overall mean; DF: degrees of freedom; CV: coefficient of variation; *: Significant at the 5% level, by the F test ($p < 0.05$); ns: Not significant, by the F test ($p < 0.05$).

In the 2021/2022 season, MBC showed estimated differences with the use of coffee husk, organic compost, and Bokashi, with values of $87.3 \mu\text{g C g}^{-1}\text{soil}$, $110 \mu\text{g C g}^{-1}\text{soil}$, and $108 \mu\text{g C g}^{-1}\text{soil}$, respectively, compared to the control, which had $181.9 \mu\text{g C g}^{-1}\text{soil}$ of MBC (Figure 8a). The reference value for this area was $187.6 \mu\text{g.C g}^{-1}\text{soil}$, indicating a reduction in MBC by 53.4%, 41.2%, and 42.2% in the respective treatments mentioned. In the second evaluated season in area 2, a general increase in MBC was observed. However, the estimated difference from the control ($365 \mu\text{g C g}^{-1} \text{ soil}$) was noted when organomineral was applied resulting in an MBC of $146 \mu\text{g C g}^{-1} \text{ soil}$, which is a reduction of $218 \mu\text{g C g}^{-1} \text{ soil}$ of MBC (Figure 8b).

Since qCO_2 is inversely related to MBC, the estimated differences were observed in the same treatments: coffee husk ($5.4 \mu\text{g C-CO}_2 \mu\text{g}^{-1} \text{ C-MBC day}^{-1}$), organic compost ($5.1 \mu\text{g C-CO}_2 \mu\text{g}^{-1} \text{ C-MBC day}^{-1}$), and Bokashi ($3.7 \mu\text{g C-CO}_2 \mu\text{g}^{-1} \text{ C-MBC day}^{-1}$), with the control having an estimated value of $1.9 \mu\text{g C-CO}_2 \mu\text{g}^{-1} \text{ C-MBC day}^{-1}$ (Figure 8c). Although urease showed a significant effect, there were no estimated differences between the soil conditioners and the control.

Figure 8: Responses of biological indicators Microbial Biomass Carbon (2021/2022 and 2022/2023) (a and b) and Soil Metabolic Quotient (2021/2022) (c) in the use of soil conditioners CH (Coffee husk), OC (Organic compost), BK (Bokashi), BC (Biochar), COMBI, OM (Organomineral) compared to a control treatment CF (Conventional fertilization), by Dunett test ($p < 0.05$), applied in a 17-year-old coffee crop– Area 2.



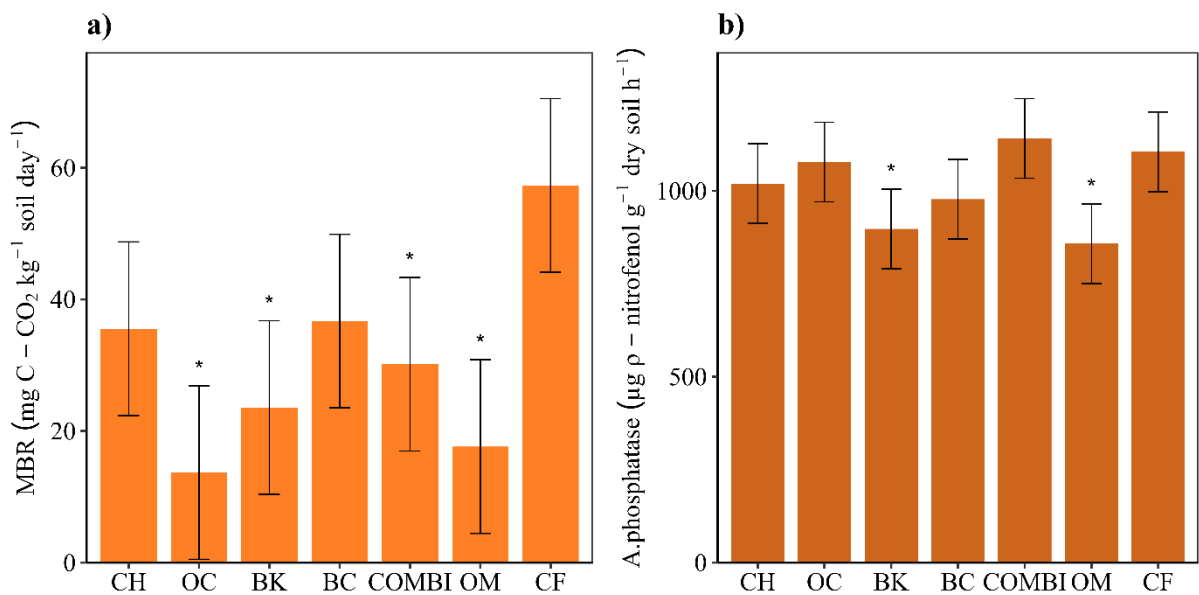
*Differential significance compared to the control treatment (FC), by Dunett test ($p < 0.05$); error bars referring to confidence intervals.

Conversely, basal soil respiration experienced a significant reduction compared to the reference value ($392 \text{ mg C-CO}_2 \text{ kg}^{-1} \text{ soil day}^{-1}$) across all treatments. The treatments with estimated differences from the control were organic compost ($13.6 \text{ mg C-CO}_2 \text{ kg}^{-1} \text{ soil day}^{-1}$), Bokashi ($23.5 \text{ mg C-CO}_2 \text{ kg}^{-1} \text{ soil day}^{-1}$), COMBI ($30.1 \text{ mg C-CO}_2 \text{ kg}^{-1} \text{ soil day}^{-1}$), and organomineral ($17.6 \text{ mg C-CO}_2 \text{ kg}^{-1} \text{ soil day}^{-1}$) (Figure 9a). The magnitude of this reduction for

the 2022/2023 season, when comparing the control (57.3 mg C-CO₂ kg⁻¹ soil day⁻¹) to the area's reference value, was an 85.4% reduction in RBM.

Acid phosphatase was the only enzyme showing a significant activity in this area, with a reduction in its enzymatic activity when compared to the area's reference value. The use of Bokashi and organomineral showed negative differences from the control treatment, with values of 887 µg p-nitrofenol.g⁻¹ dry soil.h⁻¹ for Bokashi and 875 µg p-nitrofenol.g⁻¹ dry soil.h⁻¹ for organomineral, while the estimated value in the control was 1105 µg p-nitrofenol.g⁻¹ dry soil.h⁻¹ (Figure 9b). Comparing the control with the reference value (1374 µg p-nitrofenol.g⁻¹ dry soil.h⁻¹), a there was a 19.5% reduction in the enzyme's activity.

Figure 9: Responses of biological indicators Basal Soil Respiration (a), and Acid Phosphatase (b) in the use of soil conditioners CF (Coffee husk), OC (Organic compost), BK (Bokashi), BC (Biochar), COMBI, OM (Organomineral) compared to a control treatment CF (Conventional fertilization), by Dunett test (p<0.05), applied in a 17-year-old coffee crop in the 2022/2023 season – Area 2.



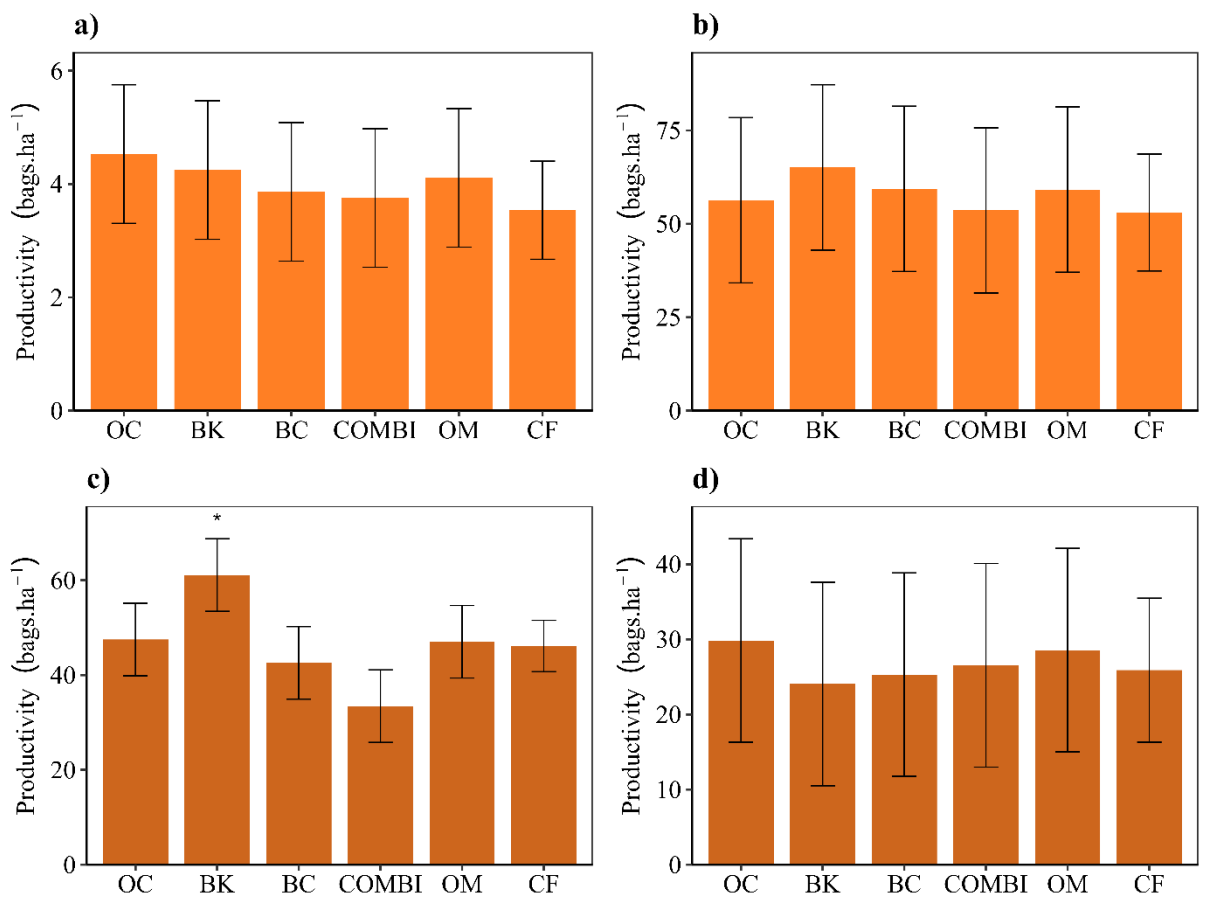
*Differential significance compared to the control treatment (FC), by Dunett test (p < 0.05); error bars referring to confidence intervals.

3.5. Productivity of coffee crop

In area 1, no significant differences were observed in both years of evaluation. The coffee crop in the 2021/2022 harvest showed lower production compared to the 2022/2023 harvest. This variation is possibly due to the biennial cycle of coffee crops, reflecting a negative year (Figure 10a) followed by a positive year (Figure 10b).

Analyzing coffee crop productivity, a significant effect was observed only in area 2 during the first year of evaluation (2021/2022) (Figure 10c). The application of biochar resulted in a productivity of 61 bags ha⁻¹ compared to 40 bags ha⁻¹ for the control, making a 34.4% increase. This significant difference may be influenced by factors beyond soil conditioner application, such as the historically high fertility of the area (Table 2). In the 2022/2023 harvest, although no significant effects were observed, there was a noticeable decrease in productivity (Figure 10d) and greater data dispersion, as indicated by wider confidence interval bars.

Figure 10: Coffee crop productivity with 7 (a,b) and 17 (c,d) years of planting in the 2021/2022 and 2022/2023 harvests, using soil conditioners CH (Coffee husk), OC (Organic compost), BK (Bokashi), BC (Biochar), COMBI, OM (Organomineral) compared to a control treatment CF (Conventional fertilization), by Dunett test ($p < 0.05$).



*Differential significance compared to the control treatment (FC), by Dunett test ($p < 0.05$); error bars referring to confidence intervals.

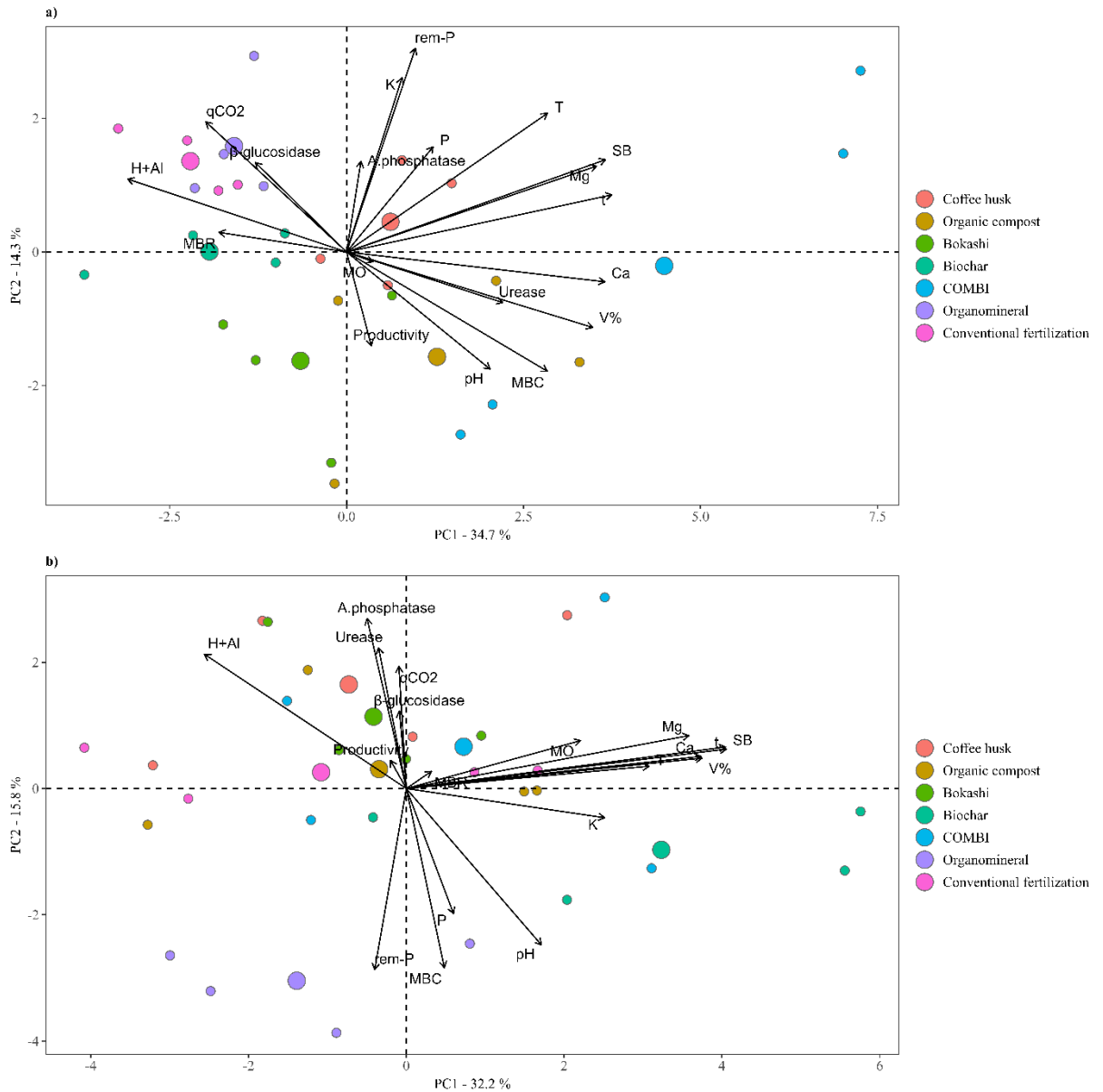
3.6. Principal Component Analysis

Despite the variability of points related to treatments, the following responses were obtained for principal component analysis (PCA) for area 1 in the 2021/2022 season showed

a total data variability of 49%, generating two principal components: PC1 – 34.7% and PC2 – 14.3% (Figure 10a). In PC1, base saturation (SB), calcium (Ca), magnesium (Mg), V%, H+Al, T, and MBC had high contributions in discriminating the treatments. In PC2, the variables remaining phosphorus (rem-P), potassium (K), qCO₂, and pH contributed most significantly to distinguishing the treatments (Figure 10a).

In the 2022/2023 season, the total data variability was 48%, with PC1 – 32.2% and PC2 – 15.8% (Figure 11b). For PC1, base saturation (SB), t, V%, Ca, magnesium (Mg), T, H+Al, and K had medium-high contributions to the discrimination of the treatments. In PC2, the variables remaining phosphorus (rem-P), microbial biomass carbon (MBC), acid phosphatase (A.phosphatase), pH, urease, and phosphorus (P) had medium-high contributions to distinguishing the treatments.

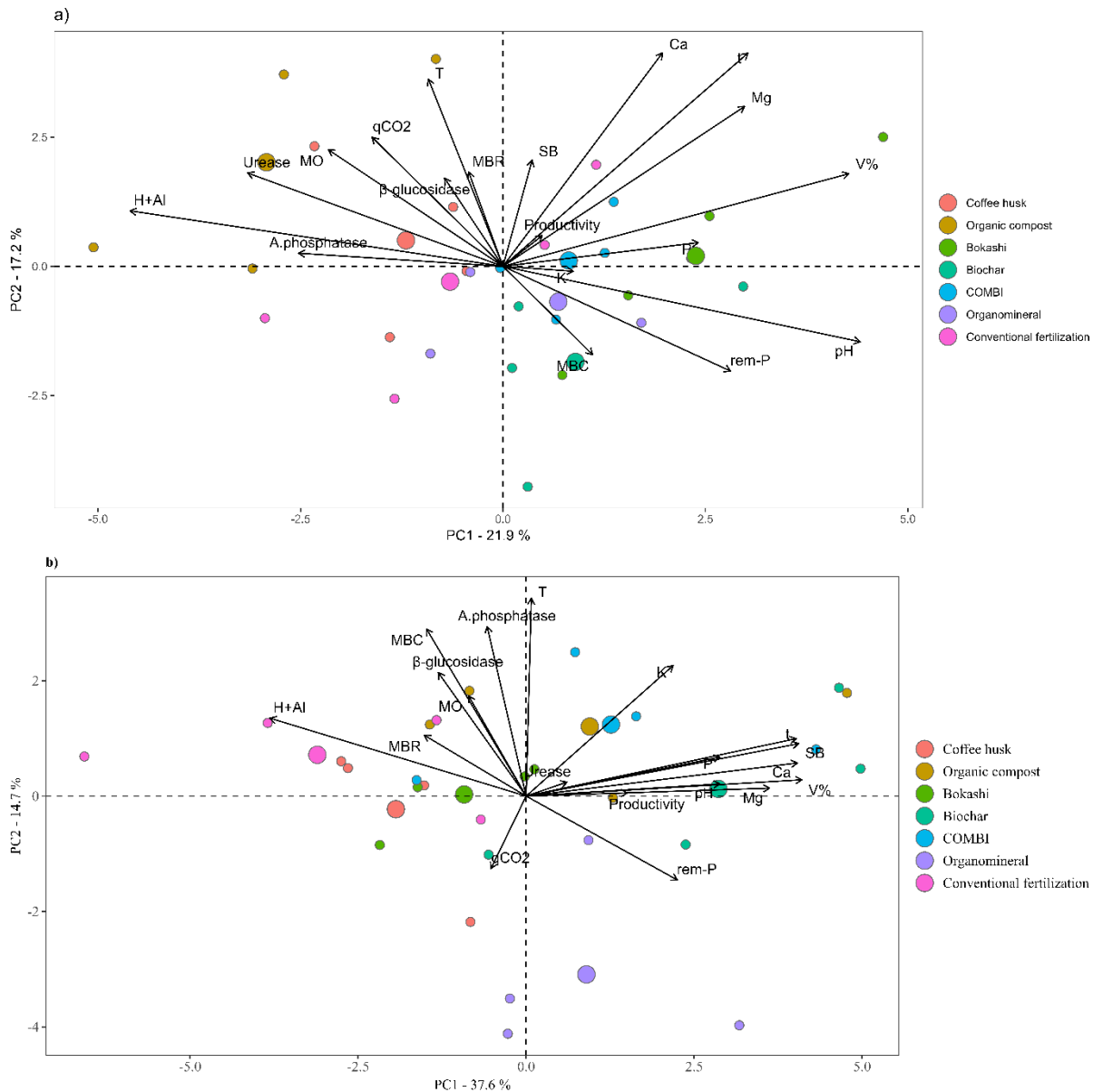
Figure 10: Principal component analysis (PCA) of chemical and biological variables in the 2021/2022 (a) and 2022/2023 (b) harvest in a coffee crop with 7 years of establishment, after application of CF soil conditioners (Coffee husk), OC (Organic compost), BK (Bokashi), BC (Biochar), COMBI, OM (Organomineral) compared to a control treatment CF (Conventional fertilization).



PCA for Area 2 in the 2021/2022 season showed a total data variability of 39%, generating two principal components: PC1 – 21.9% and PC2 – 17.2% (Figure 11a). In PC1, H+Al, pH, V%, urease, t, Mg, and rem-P had medium to high contributions to the discrimination of the treatments. In PC2, Ca), T, and qCO₂ were the variables that contributed the most to distinguishing the treatments (Figure 11a).

In the 2022/2023 season, this area exhibited the highest total data variability at 52.3%, with PC1 – 37.6% and PC2 – 14.7% (Figure 11b). For PC1, V%, SB, Ca, t, H+Al, Mg, pH, and P had high to medium contributions to the discrimination of the treatments. In PC2, T, A.phosphatase, MBCK, β -glucosidase, and OM contributed decreasingly to the distinction of the treatments.

Figure 11: Principal component analysis (PCA) of chemical and biological variables in the 2021/2022 (a) and 2022/2023 (b) harvest in a coffee crop with 7 years of establishment, after application of CF soil conditioners (Coffee husk), OC (Organic compost), BK (Bokashi), BC (Biochar), COMBI, OM (Organomineral) compared to a control treatment CF (Conventional fertilization).



4. CONCLUSION

For Area 1 in the first evaluated harvest, soil conditioners significantly enhanced chemical attributes, highlighting the importance of these treatments compared to conventional fertilization management. The treatment that most improved the soil's chemical properties was COMBI, which showed superior results over the control treatment in terms of pH, calcium (Ca), and magnesium (Mg) content, as well as base saturation, and

it also showed a lower potential acidity. From a soil fertility perspective, lower potential acidity is more desirable. In Area 2, biochar as a soil conditioner contributed the most to improved chemical attributes, particularly in phosphorus (P), potassium (K), rem-P, magnesium (Mg), and base saturation (V%)

For the biological indicators in Area 1, the soil conditioner that showed significant differences across the most variables compared to the control treatment was COMBI. It positively affected microbial biomass carbon (MBC), microbial biomass respiration (MBR), urease, and acid phosphatase. In Area 2, the application of Bokashi resulted in notable differences from the control treatment across a wider range of variables, including MBC, MBR, qCO₂, and acid phosphatase.

According to the PCA's obtained in this study, it is possible to verify that the chemical and biological attributes can be enhanced with the treatments evaluated. Demonstrating that the adoption of techniques such as aerobic and anaerobic composting, in addition to pyrolysis, can be used to transform biomass and assist in a promising management of this organic residue from coffee farming.

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Appendix

Appendix 1: Fertilization management used in the experimental areas.

AREA 1 - 2021/2022			
Inputs	Quantity	local	Month
Coffee husk	5 t ha ⁻¹	superficial	november
Organic compost	5 t ha ⁻¹	superficial	november
Bokashi	5 t ha ⁻¹	superficial	november
Biochar wood coffee	5 t ha ⁻¹	superficial	november
COMBI	5 t ha ⁻¹	superficial	november
Organomineral	2487 kg ha ⁻¹	superficial	november
Agricultural gypsum	723 kg ha ⁻¹	superficial	november
Ammonium nitrate (140 kg ha ⁻¹ of N)	518 kg ha ⁻¹	superficial	a.i
MAP (95 kg ha ⁻¹ of P ₂ O ₅)	197 kg ha ⁻¹	superficial	a.i
KCL (367 kg ha ⁻¹ of K ₂ O)	612 kg ha ⁻¹	superficial	a.i
AREA 2 - 2021/2022			
Coffee husk	5 t ha ⁻¹	superficial	november
Organic compost	5 t ha ⁻¹	superficial	november
Bokashi	5 t ha ⁻¹	superficial	november
Biochar wood coffee	5 t ha ⁻¹	superficial	november
COMBI	5 t ha ⁻¹	superficial	november
Organomineral	857 kg ha ⁻¹	superficial	november
Ammonium nitrate (140 kg ha ⁻¹ of N)	518 kg ha ⁻¹	superficial	a.i
MAP (95 kg ha ⁻¹ of P ₂ O ₅)	197 kg ha ⁻¹	superficial	a.i
KCL (367 kg ha ⁻¹ of K ₂ O)	612 kg ha ⁻¹	superficial	a.i
Dolomitic limestone	1.000 kg ha ⁻¹	superficial	november
AREA 1 - 2022/2023			
Coffee husk	10 t ha ⁻¹	superficial	november
Organic compost	10 t ha ⁻¹	superficial	november
Bokashi	10 t ha ⁻¹	superficial	november
Biochar wood coffee	10 t ha ⁻¹	superficial	november
COMBI	10 t ha ⁻¹	superficial	november
Organomineral	2328 kg ha ⁻¹	superficial	november
Ammonium nitrate (340 kg ha ⁻¹ of N)	1259 kg ha ⁻¹	superficial	a.i
Coffee husk (241 kg ha ⁻¹ of K ₂ O) + KCL	141 kg ha ⁻¹	superficial	a.i
Organic compost (326 kg ha ⁻¹ of K ₂ O) + KCL	0 kg ha ⁻¹	superficial	a.i
Bokashi (263 kg ha ⁻¹ of K ₂ O) + KCL	104 kg ha ⁻¹	superficial	a.i
Biochar wood coffee (197 kg ha ⁻¹ of K ₂ O) + KCL	213 kg ha ⁻¹	superficial	a.i
COMBI (261 kg ha ⁻¹ of K ₂ O) + KCL	106 kg ha ⁻¹	superficial	a.i
AREA 2 - 2022/2023			
Coffee husk	5 t ha ⁻¹	superficial	november
Organic compost	5 t ha ⁻¹	superficial	november
Bokashi	5 t ha ⁻¹	superficial	november

Biochar wood coffee	5 t ha ⁻¹	superficial	november
COMBI	5 t ha ⁻¹	superficial	november
Organomineral	1170 kg ha ⁻¹	superficial	november
Ammonium nitrate (260 kg ha ⁻¹ of N)	963 kg ha ⁻¹	superficial	a.i
Coffee husk (120 kg ha ⁻¹ of K ₂ O) + KCL	70 kg ha ⁻¹	superficial	a.i
Organic compost (163 kg ha ⁻¹ of K ₂ O) + KCL	0 kg ha ⁻¹	superficial	a.i
Bokashi (131 kg ha ⁻¹ of K ₂ O) + KCL	52 kg ha ⁻¹	superficial	a.i
Biochar wood coffee (98 kg ha ⁻¹ of K ₂ O) + KCL	106 kg ha ⁻¹	superficial	a.i
COMBI (130 kg ha ⁻¹ of K ₂ O) + KCL	53 kg ha ⁻¹	superficial	a.i

a.i: applied in installments