Effects of biochar-based organic microbial fertilizer on the growth and yield of Coffee (*Coffea canephora*) and Pepper (*Piper nigrum*) in Gia Lai Province

Ngo Van Long[1], Bui Phuong Anh[2*], Nguyen Duc Hanh[3], Nguyen Tuan Duong[4]
[1]*Vietnam National University of Forestry - Gia Lai Campus*
[2]*Vietnam National University of Forestry*
[3]*An Hung Gia Lai Agricultural Engineering and Trade Service Company, Branch Office*
[4]*Bac Giang Agriculture and Forestry University*

Ảnh hưởng của phân bón vi sinh hữu cơ từ than sinh học đến sự sinh trưởng và năng suất của cà phê (Coffea canephora) và hồ tiêu (Piper nigrum) tại tỉnh Gia Lai

Ngô Văn Long[1], Bùi Phương Anh[2*], Nguyễn Đức Hạnh[3], Nguyễn Tuấn Dương[4]
[1]*Trường Đại học Lâm nghiệp - Phân hiệu Gia Lai*
[2]*Trường Đại học Lâm nghiệp*
[3]*Chi nhánh Công ty TNHH Dịch vụ Kỹ thuật Nông nghiệp và Thương mại An Hưng Gia Lai*
[4]*Trường Đại học Nông - Lâm Bắc Giang*
**Corresponding author: anhbp@vnuf.edu.vn*

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ABSTRACT

This study was conducted to evaluate the effectiveness of applying biochar-based microbial organic fertilizers, produced from agricultural by-products, in improving the growth and productivity of coffee (Coffea canephora) and black pepper (Piper nigrum) in Gia Lai Province. The research employed an experimental application model in four communes: Ia Yok and Ia Sao (Ia Grai District) for coffee, and Ia Bang and Dak So Mei (Dak Doa District) for black pepper. A total of 100 tons of fertilizer (25 tons per commune) was provided to local farmers and applied following a standardized technical protocol, with control treatments using conventional chemical fertilizers. The results indicated that the application of biochar-based microbial organic fertilizers increased crop yields by 15.52% to 15.77% compared with the control. No major pest or disease outbreaks were observed during the cultivation period. The harvested products from the model showed high uniformity and notable improvements in both yield components and quality indicators. These findings confirm the potential of biochar-based microbial organic fertilizers to enhance production efficiency and product quality. The study contributes to promoting sustainable agricultural development for coffee and black pepper cultivation in Gia Lai Province and can serve as a reference model for other regions with similar conditions.

TÓM TẮT

Nghiên cứu này được thực hiện nhằm đánh giá hiệu quả của việc sử dụng phân bón hữu cơ vi sinh trên nền than sinh học, được sản xuất từ phụ phẩm nông nghiệp, trong canh tác cà phê (Coffea canephora) và hồ tiêu (Piper nigrum) tại tỉnh Gia Lai. Phương pháp nghiên cứu được triển khai thông qua mô hình ứng dụng tại bốn xã: Ia Yok và Ia Sao (huyện Ia Grai) đối với cây cà phê, Ia Bang và Đăk Sơ Mei (huyện Đăk Đoa) đối với cây hồ tiêu, với tổng lượng 100 tấn phân bón (25 tấn/xã) được cấp phát cho nông hộ và áp dụng theo quy trình kỹ thuật thống nhất; đồng thời theo dõi, so sánh với đối chứng sử dụng phân hóa học thông thường. Kết quả nghiên cứu cho thấy năng suất ở các mô hình sử dụng phân hữu cơ vi sinh trên nền than sinh học tăng từ 15,52% đến 15,77% so với đối chứng; không ghi nhận hiện tượng sâu bệnh hại nghiêm trọng trong suốt thời gian canh tác. Sản phẩm thu hoạch từ mô hình có độ đồng đều cao, các yếu tố năng suất và chỉ tiêu chất lượng được cải thiện rõ rệt. Với kết quả này, nghiên cứu khẳng định tiềm năng của phân bón hữu cơ vi sinh trên nền than sinh học trong việc nâng cao hiệu quả sản xuất và chất lượng sản phẩm, đồng thời góp phần thúc đẩy phát triển nông nghiệp bền vững đối với hai loài cây chủ lực của tỉnh Gia Lai, cũng như định hướng ứng dụng cho các khu vực có điều kiện tương đồng.

1. INTRODUCTION

Coffee (*Coffea canephora*) and black pepper (*Piper nigrum*) are two major crops with high economic value, making important contributions to the agricultural export turnover of Gia Lai Province and the Central Highlands region. However, long-term intensive cultivation with heavy dependence on chemical fertilizers has degraded soil fertility, reduced water retention capacity, caused nutrient imbalances, and increased pest and disease incidence, particularly root-related diseases. Rising fertilizer costs also place substantial pressure on producers, affecting the economic efficiency and sustainability of farming systems. In this context, the search for sustainable cultivation solutions that could ensure both yield and product quality while protecting and improving soil conditions was urgent. Microbial organic fertilizers (MOF) derived from biochar were considered a potential solution due to their ability to improve the physical and chemical properties of soil, enhance the activity of beneficial microorganisms, provide sustainable nutrient supply for crops, and contribute to reducing greenhouse gas emissions [1]. Biochar, with its porous structure and large surface area, possessed high absorption capacity, thereby improving soil health, increasing fertility and water retention, and indirectly promoting crop yields and food security [2].

In a previous study, the project developed a production model of MOF from biochar using locally available agricultural by-products with a total output of 1,000 tons [3]. The finished fertilizer met all the criteria specified in current regulations (Vietnamese National Technical Regulation QCVN 01-189:2019/BNNPTNT on fertilizer quality: organic matter content ranging from 30.61–54.20%, *Trichoderma* density from (1.1–1.5) × 10^6 CFU/g, moisture content from 24.46–28.00%, and pH from 6.78–8.14). However, the actual effectiveness of this fertilizer when applied in the field, particularly for the two major crops, coffee and black pepper in Gia Lai, had not yet been fully evaluated.

This study was conducted to assess the effects of MOF derived from biochar on the growth, yield, product quality, and pest and disease status of coffee and black pepper in selected localities of Gia Lai Province. The results of this study provided scientific evidence to recommend and scale up the application model of MOF from biochar, thereby contributing to sustainable agricultural development in the Central Highlands region.

2. RESEARCH METHODS

2.1. Research sites and duration

The study was conducted from January 2023 to April 2024 in four communes of Gia Lai Province, including Ia Yok and Ia Sao (Ia Grai District) for coffee (*Coffea canephora*), and Ia Bang and Dak So Mei (Dak Doa District) for black pepper (*Piper nigrum*). These sites were selected to represent the major cultivation areas of coffee and black pepper in the province, reflecting typical soil and climatic conditions of the Central Highlands region.

2.2. Research materials

The MOF was produced from biochar derived from the combustion of coffee tree branches and husks, combined with the *Trichoderma* biological preparation [3]. The product met the quality standards specified in the Vietnamese National Technical Regulation QCVN 01-189:2019/BNNPTNT [4] on fertilizers, ensuring that organic matter content, heavy metal concentrations, and pathogenic microorganisms were within allowable limits. In addition, the traditional organic fertilizer used in the study contained an organic matter content of 35.33%, with heavy metal values and pathogenic microorganisms also within the limits set by QCVN 01-189:2019/BNNPTNT [4] on fertilizer quality.

2.3. Experiment design

Since the experiment was not established from the beginning of the crop cycle, the microbial organic fertilizer (MOF) was applied to existing coffee (*Coffea canephora*) and black pepper (*Piper nigrum*) plantations. Two application models of MOF were established for coffee and black pepper. In each model, experiments were conducted in two stages: establishment and production. The cultivation area for each participating household was 0.5 ha. For both coffee and black pepper models, the number of participating households was 12 in the establishment stage and 8 in the production stage. The experiments were arranged using a comparative control method for each stage, consisting of three treatments:

- Treatment 1: 5 tons of traditional organic fertilizer/ha + 100% NPK according to technical recommendations;
- Treatment 2: 5 tons of microbial organic fertilizer/ha + 100% NPK;
- Treatment 3: 5 tons of microbial organic fertilizer/ha + 75% NPK.

For NPK application: the fertilizer rates per hectare for each growth stage followed the fertilization guidelines for coffee and black pepper developed by the Eakmat Center for Plant Variety Production and Supply, Western Highlands Agriculture and Forestry Science Institute [5, 6].

2.4. Fertilization protocol and model monitoring

A standardized cultivation protocol was developed for all models and was applied consistently throughout the study period.

2.4.1. Fertilization application model for coffee (Coffea canephora)

Microbial organic fertilizer (MOF) was applied following a general method: trenches were dug on both sides of the basin along the canopy projection, with the trench position changed at each application to avoid damaging the root system. After weeding and green manuring, the fertilizer was mixed well and spread into the trenches, and then covered with soil to minimize nutrient losses. MOF was applied in combination with single fertilizers (SA, urea, phosphorus - P, potassium - K) at different rates depending on the age of the trees.

a. Establishment stage

During the establishment stage, the fertilizer was applied twice a year, at the beginning and the end of the rainy season, with application rates presented in Table 1.

Table 1. Fertilizer application rates for coffee in the establishment stage

Tree age	MOF (kg/tree/year)	Combined application of single fertilizers (kg/tree/year)			
		SA	Urea	P	K
Newly planted	1.5-2	0	0.09	0.06	0.05
Year 2	2-2.5	0.01	0.12	0.10	0.06
Year 3	2-2.5	0.015	0.20	0.12	0.15

b. Production stage

In the production stage, fertilizers were applied four times per year, corresponding to the key growth stages of coffee, with application rates presented in Table 2.

Table 2. Fertilizer application rates for coffee in the production stage

No.	Application time	MOF (kg/tree)	SA (kg/tree)	Urea (kg/tree)	P (kg/tree)	K (kg/tree)	Note
1	2nd irrigation	–	0.02 (100%)	–	–	–	Entire amount of SA
2	Early rainy season (Mar-May)	1.5–1.75 (50%)	–	0.14 (35%)	–	0.12 (30%)	With MOF
3	Mid rainy season (Jul-Aug)	1.5–1.75 (50%)	–	0.16 (40%)	0.12 (40%)	0.16 (40%)	With MOF
4	Sep-Oct	–	–	0.10 (25%)	0.18 (60%)	0.12 (30%)	3 applications, 10 days apart
Total		**3–3.5**	**0.02**	**0.40**	**0.30**	**0.40**	

c. Monitoring and data collection

Establishment stage: Soil samples were taken from the 0–20 cm layer before the experiment and after each harvest season to analyze the following parameters: pH, organic carbon (OC), total N, P, K, Ca, Mg, cation exchange capacity (CEC), base saturation, soil texture, bulk density, particle density, and porosity. For the plants, growth and development indicators were monitored, including plant height, stem diameter, number of primary branch pairs, length of primary branches, and the rate of leaf yellowing.

Production stage: In addition to soil parameters analyzed as in the establishment stage, plant monitoring focused on yield components and coffee productivity. The indicators included fruit set rate, weight of 100 beans, fresh fruit yield, fresh-to-bean ratio, and bean yield. The effectiveness of MOF was evaluated by comparing these indicators among different fertilization treatments.

2.4.2. Fertilizer application model for black pepper (Piper nigrum)

MOF application for black pepper was carried out using a common method: fertilizers were broadcasted on the soil surface at a distance of 40–60 cm from the base, under the canopy. When the soil was dry, irrigation was applied prior to fertilization to enhance nutrient uptake. The microbial organic fertilizer (MOF) was used in combination with single fertilizers (SA, urea, phosphorus, potassium), with application rates and mixing methods adjusted according to each growth stage of black pepper.

a. Establishment stage

For newly planted black pepper, MOF was applied as basal fertilization 15–20 days before planting, at a rate of 2.5–3.0 kg per stake, combined with two-thirds of the prescribed phosphorus dosage per planting hole. In addition, lime powder was applied at 500 kg/ha/year, evenly spread on the soil surface under the canopy projection to improve soil conditions and reduce soil-borne pathogens. During cultivation, top-dressing fertilizers were applied in the first and second years, with application rates presented in Table 3 and Table 4.

Table 3. Fertilizer application rates for black pepper in the establishment stage

Tree age	MOF (kg/stake/year)	Combined application of single fertilizers (kg/stake/year)			
		SA	Urea	P	K
Newly planted	1.5-2	0.05	0.12	0.25	0.10
Year 2	2-2.5	0.10	0.20	0.30	0.20

Table 4. Top-dressing application in the black pepper model during the establishment stage

No.	Application time	MOF	SA	Urea	P	K
1	20–30 days after planting	1/3	100%	1/3	2/3	1/3
2	2–3 months after planting	1/3	–	1/3	1/3	1/3
3	End of rainy season	1/3	–	1/3	1/3	1/3

b. Production stage

During the production stage, fertilization is carried out four times per year, corresponding to the main growth phases of pepper plants; the specific application rates and application methods are presented in Table 5.

Table 5. Fertilizer application rates used in black pepper cultivation model during the production stage

No.	Application time	MOF	SA	Urea	P	K
1	Beginning of rainy season, after harvesting	60%	100%	1/4	1/4	1/4
2	Buds initiation	40%	–	1/4	1/2	1/4
3	Fruits set	–	–	1/4	1/4	1/4
4	Fruits ripening	–	–	1/4	–	1/4
Total	All year (kg/stake/year)	2.0–2.5	0.10	0.35	0.50	0.45

c. Monitoring and data collection

Soil and plant indicators were measured following standard methods; same parameters were applied for both crops except yield components. Soil sampling was conducted at a depth of 0–20 cm before the experiment and after each harvest season. Soil parameters analyzed included: pH, organic carbon (OC), total nitrogen (N), total phosphorus (P), total potassium (K), calcium (Ca), magnesium (Mg), cation exchange capacity (CEC), base saturation, soil texture, bulk density, particle density, and porosity. For the plants, key growth indicators were monitored, including plant height, canopy diameter, and the rate of yellowing leaves.

In addition, detailed observations were made on yield components and pepper productivity.

2.5. Data analysis and processsing

The collected data were compiled and analyzed using descriptive statistical methods. For soil, indicators were compared before and after the experiment to evaluate changes caused by the application of MOF. For crops, growth, development, and yield indicators were calculated as mean values and the percentage differences in yield (%) among fertilization treatments. The sampling process, including the number of households sampled and the sampling method, was carried out in collaboration with the Institute for Agricultural Environment (IAE) under the Vietnam Academy of Agricultural Sciences (VAAS). All soil analyses were performed at the IAE Laboratory according to national standards for agricultural soil testing.

3. RESULTS AND DISCUSSION

3.1. Fertilization application model for coffee (*Coffea canephora*)

3.1.1. Establishment stage

Table 6. Effect of MOF on the growth factors of coffee trees during the establishment stage

Treatment	Indicator				
	Plant height (cm)	Stem diameter (cm)	No. of primary branch pairs	Length of primary branch (cm)	Yellow-leaf rate (%)
Treatment 1	119.35 ± 3.03	5.60 ± 0.12	19.29 ± 0.94	81.47 ± 2.04	4.98 ± 0.08
Treatment 2	125.63 ± 3.11	5.90 ± 0.15	20.31 ± 0.91	85.75 ± 2.19	4.74 ± 0.05
Treatment 3	125.60 ± 2.96	5.89 ± 0.17	20.22 ± 0.88	85.73 ± 1.94	4.73 ± 0.04

Data from Table 6 on the evaluation of the effects of MOF on the growth factors of coffee trees in the establishment stage show that, after applying fertilizers at different application rates in 3 treatments, the values of the growth indicators of coffee trees in the establishment stage were not the same.

Compared with Treatment 1, Treatment 2 increased tree height by 6.28 cm, stem diameter by 0.29 cm, the number of primary branch pairs by 1.02 pairs, primary branch length by 4.29 cm, and reduced the rate of yellow-leaf trees by 0.24%. Treatment 3 had a similar effect: tree height increased by 6.25 cm, stem diameter by 0.29 cm, the number of primary branch pairs by 0.93 pairs, primary branch length by 4.27 cm, and the rate of yellow-leaf trees decreased by 0.25%.

Comparing the values of the growth indicators of coffee trees in the establishment stage between Treatment 2 and Treatment 3, the results showed that the values of the growth indicators of coffee trees between these two treatments were not significant. Therefore, the use of MOF from the Project can contribute to reducing the amount of NPK fertilizer used by up to 25%.

In addition to evaluating the effects of MOF on growth factors, the Project team also collected soil samples from the experimental treatments to assess the effects of MOF on soil quality and soil texture of coffee cultivation during the establishment stage. The results are shown in Table 7 and Table 8.

The values of soil physico-chemical indicators in coffee cultivation during the establishment stage under different fertilization treatments showed positive changes compared to the pre-application stage, indicating the effectiveness of fertilizer use in improving soil quality. A comparison among the fertilizer treatments revealed that some soil indicators such as pH, bulk density, and porosity showed no significant differences among treatments. However, the application of different fertilizer types and dosages had a clear impact on organic carbon (OC), nutrients (N, P, K), and cation exchange capacity.

The OC content in the treatments applying MOF increased by 0.13–0.15% compared to the control treatment that used traditional organic fertilizer. In Treatment 1 and Treatment 2, which applied 100% NPK, the analyzed nutrient contents were relatively equivalent; however, in Treatment 3, which applied 75% NPK, the nutrient contents decreased, though this reduction did not negatively affect the growth indicators of coffee plants during the establishment stage, possibly because the reduced level still met the nutrient demand of the plants.

Table 7. Physico-chemical indicators of coffee cultivation soil in the establishment stage

No.	Indicator	Unit	Pre-experiment	Treatment 1	Treatment 2	Treatment 3
1	pH	-	5.51 ± 0.24	5.56 ± 0.32	5.55 ± 0.19	5.58 ± 0.22
2	OC	%	2.24 ± 0.43	2.31 ± 0.56	2.46 ± 0.72	2.44 ± 0.68
3	N	mg/g	1.62 ± 0.19	1.74 ± 0.18	1.76 ± 0.11	1.68 ± 0.20
4	P	mg/g	71.82 ± 6.45	78.56 ± 7.09	79.92 ± 6.12	71.86 ± 6.72
5	K	mg/g	80.78 ± 13.11	118.22 ± 13.54	119.02 ± 14.63	98.86 ± 12.88
6	Ca	mg/kg	13.15 ± 2.19	55.25 ± 3.87	54.68 ± 4.02	55.08 ± 3.90
7	Mg	mg/kg	359.20 ± 23.21	417.22 ± 26.54	416.65 ± 22.99	419.81 ± 24.75
8	CEC	meq/100g	10.28 ± 1.01	11.09 ± 0.88	15.67 ± 0.95	15.49 ± 1.11
9	BS	%	32.73 ± 3.65	37.91 ± 3.72	38.04 ± 3.57	37.87 ± 3.63
10	BD	g/cm^3	0.82 ± 0.10	0.91 ± 0.08	0.90 ± 0.06	0.91 ± 0.07
11	PD	g/cm^3	2.12 ± 0.18	2.50 ± 0.25	2.49 ± 0.20	2.51 ± 0.23
12	Porosity	%	61.32 ± 8.09	63.60 ± 7.43	63.86 ± 8.02	63.74 ± 7.66

Table 8. Soil texture composition of coffee cultivation during the establishment stage

Soil texture composition (%)	Before experiment	Treatment 1	Treatment 2	Treatment 3
Sand	22.45 ± 2.05	22.66 ± 1.89	22.77 ± 1.94	22.69 ± 1.80
Silt	37.87 ± 4.66	39.65 ± 4.59	38.96 ± 4.98	39.05 ± 4.55
Clay	39.70 ± 3.88	41.22 ± 3.90	42.06 ± 4.01	41.68 ± 3.93

Regarding CEC, a clear difference was recorded in the treatments using MOF compared to those using traditional organic fertilizer. This phenomenon can be explained by the presence of biochar in MOF, which, as reported in previous studies, significantly contributes to improving the soil's cation exchange capacity [7]. The application of MOF produced with biochar under the project increased CEC in the soil from 4.4–4.58 meq/100 g, equivalent to an increase of 39.68 - 41.30% compared to traditional organic fertilizer without biochar.

3.1.2. Production stage

Table 9. Effect of MOF on the growth factors of coffee trees during the production stage

Treatment	Indicator					Increase in clean bean yield compared to control (%)
	Fruit set rate (%)	Fruit weight (g/100 fruits)	Fresh fruit yield (tons/ha)	Fresh-to-bean ratio	Clean bean yield (tons/ha)	
Treatment 1	70.03 ± 4.42	81.45 ± 6.04	15.73 ± 1.06	3.93 ± 0.67	3.48 ± 0.43	-
Treatment 2	80.76 ± 4.48	93.63 ± 6.10	18.14 ± 1.02	4.52 ± 0.62	4.01 ± 0.39	15.23
Treatment 3	80.90 ± 4.39	93.64 ± 6.09	18.12 ± 1.12	4.51 ± 0.64	4.02 ± 0.35	15.52

Coffee yield is determined by indicators such as fruit set rate and fruit weight. Different fertilizer treatments resulted in variations in these yield components. Data presented in Table 9 show clear differences between the treatment using traditional organic fertilizer and those applying the project's MOF.

Specifically, the fruit set rate in Treatment 2 and Treatment 3 (with MOF application) increased by 10.77 - 10.87% compared with the control. The weight of 100 fruits rose by 12.18–12.19 g, equivalent to 14.95–14.96%. These differences led to fresh coffee fruit yields of 2.39 - 2.41 tons/ha. The application of MOF also increased the fresh-to-bean ratio to 0.58 - 0.59, representing an improvement of 14.75–15.01%, and clean bean yields reached 0.53 - 0.54 tons/ha, an increase of 15.23–15.52% compared with the traditional organic fertilizer treatment currently used by farmers.

Comparison of yield component values and final yields between Treatment 2 and Treatment 3 revealed no significant differences, indicating that the use of MOF can reduce the amount of inorganic fertilizer by 25% without affecting coffee yield, thereby significantly saving production costs for farmers. The differences in yield components and overall yield were attributed to variations in fertilizer application, which altered soil quality among the experimental treatments.

Table 10. Physico-chemical indicators of coffee cultivation soil in the production stage

No.	Indicator	Unit	Pre-experiment	Treatment 1	Treatment 2	Treatment 3
1	pH	-	4.36 ± 0.22	4.45 ± 0.20	4.47 ± 0.25	4.44 ± 0.18
2	OC	%	2.21 ± 0.36	2.39 ± 0.34	2.79 ± 0.38	2.75 ± 0.41
3	N	mg/g	1.68 ± 0.11	1.85 ± 0.13	1.86 ± 0.15	1.77 ± 0.12
4	P	mg/g	54.13 ± 5.12	77.86 ± 5.26	77.59 ± 6.00	73.53 ± 5.55
5	K	mg/g	62.99 ± 9.05	98.86 ± 10.11	98.11 ± 10.68	86.09 ± 9.73
6	Ca	mg/kg	10.41 ± 1.05	11.32 ± 1.64	11.28 ± 1.23	11.09 ± 1.41
7	Mg	mg/kg	361.30 ± 9.88	392.16 ± 10.24	390.07 ± 9.75	393.64 ± 10.66
8	CEC	meq/100g	12.23 ± 10.91	13.47 ± 1.03	14.99 ± 1.05	15.02 ± 0.89
9	BS	%	34.66 ± 2.92	35.24 ± 3.09	35.56 ± 3.17	35.33 ± 3.05
10	BD	g/cm^3	1.02 ± 0.06	1.08 ± 0.07	1.10 ± 0.08	1.08 ± 0.08
11	PD	g/cm^3	2.41 ± 0.25	2.53 ± 0.30	2.55 ± 0.25	2.55 ± 0.29
12	Porosity	%	57.03 ± 7.24	58.60 ± 6.98	59.22 ± 7.09	59.19 ± 7.15

Table 11. Soil texture composition of coffee cultivation during the production stage

Soil texture composition (%)	Before experiment	Treatment 1	Treatment 2	Treatment 3
Sand	15.73 ± 1.68	17.48 ± 1.80	17.53 ± 1.67	17.40 ± 1.85
Silt	27.49 ± 2.00	29.06 ± 2.51	29.32 ± 2.62	29.26 ± 2.57
Clay	56.79 ± 4.09	58.02 ± 4.15	57.98 ± 3.90	58.11 ± 4.22

Similar to the fertilization model applied to coffee during the establishment stage, the use of fertilizers in the model for coffee at the production stage also resulted in positive changes in soil properties. However, the variation in fertilizer dosage also led to differences in the values of soil quality indicators.

The main component of soil organic matter is organic carbon. Total OC refers to the amount of carbon in materials derived from living organisms and plants; the storage of OC in soil can improve soil quality [8, 9]. Data in Table 10 indicate changes in the organic carbon content of soil in treatments. Specifically, compared with the control treatment, the organic carbon content increased from 0.36% to 0.40%, which forms the basis for improving productivity-related indicators and coffee yield.

The cation exchange capacity (CEC) values of soil were also significantly improved. In Treatment 2 and Treatment 3, CEC reached 14.99 and 15.02 meq/100 g soil, respectively, increasing by 1.52 and 1.55 meq/100 g soil compared with the control treatment, equivalent to an increase of 11.28% and 11.50%.

Changes in the values of nutrient content indicators in soil also influenced the productivity-related indicators of coffee. According to the study of Roelofsen and Coolhass (cited by Clifford and Willson, 1987) [10], to produce 1 ton of coffee beans, it requires 35 kg N, 6 kg P_2O_5, 50 kg K_2O, 4 kg CaO, 4 kg MgO, and several other secondary and trace elements. In Treatment 1 and Treatment 2, the same amount of NPK was applied, so the contents of total N, P, K in soil were similar. Meanwhile, by applying only 75% of the NPK amount, Treatment 3 led to slightly lower levels of total nitrogen, phosphorus, and potassium in the soil. However, this difference did not affect the productivity-related indicators or the coffee yield, as shown in Table

9. Therefore, it can be concluded that the application of MOF fertilizers under the Project helped save 25% of the required inorganic fertilizer.

3.2. Fertilization application model for black pepper (*Piper nigrum*)

3.2.1. Establishment stage

Table 12. Effect of MOF on the growth factors of black pepper trees during the establishment stage

Treatment	Indicators		
	Plant height (cm)	Canopy diameter (cm)	Yellow-leaf rate (%)
Treatment 1	173.86 ± 4.68	105.92 ± 6.06	3.52 ± 0.12
Treatment 2	175.19 ± 5.65	107.03 ± 7.12	3.49 ± 0.17
Treatment 3	174.94 ± 6.24	106.66 ± 6.87	3.54 ± 0.20

Data in Table 12 show that the values of growth parameters of pepper plants, including plant height, canopy diameter, and leaf yellowing rate, did not differ among the experimental treatments.

The different treatments with varying types and amounts of fertilizers did not alter the growth parameters of pepper plants, indicating that the nutritional requirements during the establishment stage were adequately met.

Table 13. Physico-chemical indicators of black pepper cultivation soil in the establishment stage

No.	Indicator	Unit	Pre-experiment	Treatment 1	Treatment 2	Treatment 3
1	pH	-	4.91 ± 0.14	4.96 ± 0.10	4.97 ± 0.13	5.01 ± 0.15
2	OC	%	1.81 ± 0.05	2.01 ± 0.10	2.22 ± 0.08	2.20 ± 0.06
3	N	mg/g	1.51 ± 0.08	1.82 ± 0.09	1.84 ± 0.08	1.72 ± 0.11
4	P	mg/g	89.67 ± 4.22	130.44 ± 5.06	129.56 ± 4.85	120.14 ± 4.93
5	K	mg/g	129.59 ± 6.05	194.67 ± 6.65	202.65 ± 6.13	191.39 ± 6.79
6	Ca	mg/kg	158.11 ± 5.16	368.8 ± 5.55	374.6 ± 5.32	334.8 ± 5.39
7	Mg	mg/kg	897.60 ± 18.11	984.41 ± 19.82	990.6 ± 17.31	990.8 ± 18.25
8	CEC	meq/100g	11.5 ± 1.19	12.0 ± 1.33	15.8 ± 1.61	15.7 ± 1.22
9	BS	%	39.64 ± 3.99	40.12 ± 3.20	39.81 ± 3.47	40.05 ± 3.51
10	BD	g/cm^3	0.78 ± 0.09	0.86 ± 0.07	0.87 ± 0.09	0.86 ± 0.11
11	PD	g/cm^3	2.07 ± 0.06	2.44 ± 0.09	2.45 ± 0.12	2.43 ± 0.08
12	Porosity	%	62.13 ± 6.42	64.75 ± 6.77	64.49 ± 6.30	64.61 ± 6.15

Table 14. Soil texture composition of black pepper cultivation during the establishment stage

Soil texture composition (%)	Before experiment	Treatment 1	Treatment 2	Treatment 3
Sand	13.30 ± 1.99	13.50 ± 1.78	15.50 ± 1.90	15.47 ± 1.88
Silt	28.67 ± 3.74	32.51 ± 3.66	33.84 ± 3.62	33.80 ± 3.59
Clay	52.20 ± 8.60	54.28 ± 8.55	55.52 ± 8.71	55.51 ± 8.68

Data in the two tables indicate that most soil quality parameters were generally comparable among the experimental treatments, with the exception of OC, CEC, and nutrient contents, which showed relatively large differences. These findings are consistent with the results observed in the coffee fertilization experiment.

For OC, the application of fertilizers increased soil organic carbon content from 0.20% to 0.41% compared with pre-experiment levels, highlighting the positive impact of fertilization on soil quality. Among treatments, OC values in Treatments 2 and 3, were 0.19–0.21% higher than in Treatment 1, which used conventional organic fertilizer.

With CEC, clear differences were observed between treatments applying MOF and the treatment with conventional organic fertilizer. This can be explained by the presence of biochar as a raw material in MOF, which is known to significantly enhance soil CEC [7]. Application of biochar-based MOF increased soil CEC by 3.7–3.8 meq/100 g .

3.2.2. Production stage

Nutrients are critical factors determining the yield of black pepper. The economically most effective fertilizer rate for pepper is 300 kg N – 150 kg K_2O – 225 kg P_2O_5 per hectare, combined with 10 kg of farmyard manure per pepper stake per year [11]. The results of fertilizer application on yield components and the yield of black pepper during the production stage in Gia Lai are presented in Table 15.

Table 15. Effect of MOF on the growth factors of black pepper trees during the production stage

Treatment	Indicator					Increase in dry pepper yield compared to control (%)
	Number of new branches (branches)	Number of spikes per stake (spikes)	Bulk density (g/L)	Fresh spike yield (kg/stake)	Dry pepper yield (tons/ha)	
Treatment 1	138.22 ± 14.54	2443.8 ± 78.4	515.3 ± 13.6	8.33 ± 0.79	3.55 ± 0.20	-
Treatment 2	158.79 ± 12.99	2,544.6 ± 86.0	538.1 ± 15.2	9.59 ± 0.88	4.11 ± 0.19	15.77
Treatment 3	158.22 ± 13.60	2,542.0 ± 91.9	538.3 ± 14.1	9.58 ± 0.65	4.10 ± 0.15	15.49

Data in the above table show that the application of the Project's MOF in Treatment 2 (5 tons MOF + 100% NPK) and Treatment 3 (5 tons MOF + 75% NPK) resulted in better performance compared with Treatment 1 (5 tons conventional organic fertilizer + 100% NPK). This effect was clearly reflected in the growth indicators: the number of new branches in Treatments 2 and 3 exceeded that of Treatment 1 by 14.47–14.88%. Similarly, the number of spikes per stake in these two treatments was higher than in the control by 98.2–100.8 spikes. Bulk density also improved, reaching 22.80–23.20 g/L, which was 4.42–4.50% higher than in the control treatment.

Beyond growth indicators, yield components in the treatments applying MOF also outperformed those with conventional organic fertilizer, leading to a marked increase in pepper productivity. Specifically, fresh spike yield in Treatments 2 and 3 was 1.25–1.26 kg/stake higher, corresponding to a 15.01–15.13% increase. Dry pepper yield also rose by 15.49–15.77%.

A comparison between Treatment 2 and Treatment 3 revealed no significant differences in yield components. This finding confirms that the application of the Project's MOF can reduce the required NPK input by up to 25% while maintaining stable and efficient pepper yields.

Table 16. Physico-chemical indicators of black pepper cultivation soil in the production stage

No.	Indicator	Unit	Pre-experiment	Treatment 1	Treatment 2	Treatment 3
1	pH	-	4.65 ± 0.10	4.68 ± 0.10	4.66 ± 0.09	4.67 ± 0.12
2	OC	%	2.02 ± 0.08	2.31 ± 0.09	2.55 ± 0.12	2.57 ± 0.07
3	N	mg/g	1.53 ± 0.05	1.67 ± 0.07	1.68 ± 0.06	1.62 ± 0.05
4	P	mg/g	84.72 ± 2.45	97.06 ± 3.00	96.96 ± 2.81	90.58 ± 3.07
5	K	mg/g	154.04 ± 4.33	167.25 ± 3.99	168.50 ± 4.10	161.44 ± 3.74
6	Ca	mg/kg	347.50 ± 9.43	379.40 ± 8.69	378.98 ± 7.80	340.21 ± 8.94
7	Mg	mg/kg	419.20 ± 12.08	936.70 ± 11.86	938.36 ± 12.01	937.44 ± 13.05
8	CEC	meq/100g	12.21 ± 1.03	12.35 ± 1.17	15.04 ± 1.05	15.10 ± 1.18
9	BS	%	36.78 ± 1.32	37.02 ± 1.21	36.89 ± 1.40	37.10 ± 1.01
10	BD	g/cm^3	1.11 ± 0.05	1.16 ± 0.06	1.17 ± 0.04	1.16 ± 0.05
11	PD	g/cm^3	2.35 ± 0.12	2.55 ± 0.14	2.54 ± 0.13	2.54 ± 0.10
12	Porosity	%	52.77 ± 3.66	54.51 ± 3.42	53.94 ± 4.55	54.33 ± 3.92

Table 17. Soil texture composition of black pepper cultivation during the production stage

Soil texture composition (%)	Before experiment	Treatment 1	Treatment 2	Treatment 3
Sand	12.37 ± 1.27	13.06 ± 1.04	13.22 ± 1.17	13.15 ± 1.22
Silt	27.97 ± 2.55	30.26 ± 2.49	30.34 ± 2.60	30.30 ± 2.51
Clay	55.45 ± 5.88	56.33 ± 5.32	56.40 ± 5.66	56.35 ± 5.67

The application of the project's MOF fertilizer increased the soil organic carbon content by 0.24–0.26% compared to the formula using traditional organic fertilizer. At the same time, CEC values also recorded an increase of 2.69–2.75 meq/100 g soil, compared to the control formula.

4. CONCLUSION

The research results demonstrate that the application of biochar-based microbial organic fertilizer in coffee and pepper cultivation in Gia Lai province delivered significant improvements in both yield and product quality. Yields in the MOF treatment formulas were 15.52% to 15.77% higher than the control, while harvested products showed greater uniformity and improved yield components.

These findings confirm the potential of biochar-based microbial organic fertilizer in enhancing production efficiency, improving crop quality, and reducing dependence on chemical fertilizers. This represents a suitable approach for promoting sustainable agriculture in the Central Highlands region. To optimize efficiency and expand application, further large-scale and long-term studies are necessary to fully assess the impacts of this fertilizer on soil fertility, economic efficiency, and resilience to climate change [12, 13].

This study was conducted within a limited time frame; therefore, comprehensive evaluations of fertilizer efficiency, product quality, and long-term sustainability were not included. These aspects will be addressed in subsequent research to provide a more complete assessment of the agronomic and environmental impacts of biochar-based microbial organic fertilizer application.

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