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Physicochemical characterization of coffee pulp-derived biochar and its effects on soil abiotic and biotic properties

Piyaphad Ninlaphong[a], Kesinee Iamsaard[b], Sasiprapa Kullachonphuri[a], Phonlawat Soilueang[a], Yupa Chromkaew[a], Metinee Nakdee[a,c], Toungporn Uttarotai[d], Yaoliang Chen[e], Nuttapon Khongdee[d,*]

[a] Department of Plant and Soil Science, Faculty of Agriculture, Chiang Mai University, Chiang Mai 50200, Thailand
[b] Department of Natural Resources and Environment, Faculty of Agriculture, Natural Resources and Environment, Naresuan University, 65000, Thailand
[c] Faculty of Science and Agricultural Technology, Rajamangala University of Technology Lanna, Lampang 52000, Thailand
[d] Department of Highland Agriculture and Natural Resources, Faculty of Agriculture, Chiang Mai University, Chiang Mai 50200, Thailand
[e] School of Geographical Sciences, Fujian Normal University, Fuzhou 350117, China

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ABSTRACT

Coffee processing waste, particularly coffee pulp, has been accumulating at increasing rates, resulting in substantial environmental concerns. Unfortunately, comprehensive documentation of effective waste management approaches is still lacking. Therefore, this study aims to assess the effectiveness of coffee pulp-derived biochar on agricultural soil health by examining its influence on several soil parameters, including nutrient content, physicochemical properties, and microbial activity. The experimental design was a Completely Randomized Design, consisting of five treatments. The approaches entailed incorporating coffee pulp-derived biochar into soil at proportions of 0, 2.50, 3.75, 5.00, and 7.50 % of the soil's weight. The characterization of biochar was analyzed by scanning electron microscope (SEM), Energy Dispersive X-Ray Spectroscopy (EDS), and Fourier-transform infrared spectroscopy (FTIR). Results showed the coffee pulp biochar contains various pore's structure and high spectra of –C–O stretching functional group. High carbon (C) content (66.60 %) and abundance of exchangeable K were detected in as-made biochar. The analysis of basic soil nutrients after treatment with coffee biochar revealed statistically significant differences ($P \leq 0.05$) in available P exchangeable K, exchangeable Mg (highest at 7.5 %), exchangeable Ca (highest at 5 %), and %SOM (increased at 3.75 %). Notably, soil microbial respiration (SMR) and dissolved organic carbon (DOC) increased proportionally with the percentage of coffee biochar used. Conversely, microbial biomass carbon (MBC) decreased as the dosage of coffee biochar increased. Microbial analysis revealed reduced fungal counts (max 68 % at 5 % biochar) and increased cellulase-producing (39 %) and phosphate-solubilizing (14 %) microorganisms at 2.5 % biochar compared to control. The correlation matrix has evidenced significant exchangeable K content in coffee pulp biochar demonstrating the positive correlation with soil biological improvement. Coffee pulp biochar produced from traditional kiln considerably enhances soil characteristics and modifies microbial populations.

1. Introduction

Improperly processed agricultural waste would not only result in significant loss of renewable resources but also present major environmental risks, such as increased emissions of greenhouse gases (GHGs), water pollution, and land degradation (Xu et al., 2024). The World Health Organization states that 21 % of GHGs are caused by the ongoing burning of agricultural waste (Singh and Jadeja, 2024). Therefore, the above-mentioned problem needs to be concentrated for reducing the gaining of the GHGs emission from agricultural waste burning. In this case, coffee waste is one of the current issues that need to be considered. This is due to the increasing global demand for coffee resulting the huge waste generating annually. Normally, coffee pulp is often disposed of in landfills, leading to significant environmental and health issues. Coffee pulp refers to the solid debris that is mostly produced during the wet processing of arabica coffee cherries. It accounts for approximately 50 %

* Corresponding author.
E-mail address: nuttapon.k@cmu.ac.th (N. Khongdee).

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of the total amount of the mature fruit (Ameca et al., 2018). Presently, worldwide coffee consumption has been rising at an average pace above 2 % per annum during the past decade (Quadra et al., 2020). The Thai coffee business shown development from 2016 to 2020. The annual average demand for coffee beans in Thailand is around 79,000 tons (Soilueang et al., 2023). In the coffee processing, biological losses are estimated at 40–45 %, encompassing pulp, husk, parchment, silver skin, and wasted coffee grounds (Esquivel and Jimenez, 2012). Coffee pulp constitutes up to 29 % of the total dry weight, resulting in waste disposal that contributes to environmental contamination and incurs substantial management costs (Aristizábal-Marulanda et al., 2017). Improper decomposition of coffee pulp results in the release of carbon dioxide (CO_2), nitrates (NO_3^-), sulfates (SO_4^{2-}), and phosphates (PO_4^{3-}), which might potentially pollute surface water. Coffee pulp contains significant amounts of carbon-rich compounds like cellulose, hemicellulose, lignin, proteins, and sugars. When these decompose properly through controlled composting, much of this C can be incorporated into stable soil organic matter. Improper management shifts the balance toward atmospheric carbon release instead of carbon sequestration (Pongsiriyakul et al., 2024). To mitigate the environmental impact and alleviate waste management challenges, researchers have developed methods to extract and valorize bioactive compounds from coffee pulp, including polyphenols, caffeine, and pectin, which have potential applications in food, pharmaceutical, and cosmetic industries (Hu et al., 2023; Manasa et al., 2021).

A method to leverage agricultural waste is through value addition. It has recently been utilized to manufacture diverse materials intended to address environmental issues. Biochar produced from agricultural waste has been extensively researched over the past decade owing to its distinctive features and performance efficiency. Biochar has been extensively utilized to enhance soil quality. Utilizing biochar in soil represents an innovative approach to repurpose agricultural waste. Biochar is an affordable and eco-friendly material that enhances agricultural productivity and mitigates soil contamination (Oni et al., 2019; Khan et al., 2024). In China, soil amendment with biochar by pyrolyzing wheat straw increased rice yields by 12–14 % (Zhang et al., 2010). Moreover, biochar application has been shown to increase microbial abundance and diversity, improve water retention and air circulation, enhance soil structure and aggregation, promote plant growth and root development, stimulate the production of beneficial soil enzymes and metabolites. These effects are primarily attributed to biochar's high surface area, porous structure, and capacity to adsorb and retain nutrients (de Jesus Duarte et al., 2019; Głąb et al., 2016; Lyu et al., 2022). In terms of the environment, biochar may reduce the absorption of toxic elements such as various heavy metals, contaminated soil, and toxic compounds (Herath et al., 2013; Iamsaard et al., 2022; Khan et al., 2014; Lehmann, 2007).

The utilization of coffee pulp biochar has been linked to elevated soil pH and reduced soil EC. This is essential for enhancing the growing conditions for crops, especially in saline-alkali soils. Biochar treatments have shown a decrease in soil salinity and pH levels, hence improving nutrient availability and facilitating enhanced root growth (Zuo et al., 2022). While, previous study reported that coffee pulp biochar enhances the availability of vital nutrients, including P, K, and N in the soil (Gu et al., 2023). In addition, biochar serves as a phosphorus supply and modifies its solubility via pH alterations, thereby improving nutrient absorption by plants (Huang et al., 2023). Studies demonstrate that using coffee pulp biochar can improve nutrient cycling and availability, essential for plant development. It has been demonstrated to enhance the physical, chemical, and biological properties of soils utilized for coffee growth (Sánchez-Reinoso et al., 2023). Research indicates that 5 % application of coffee pulp biochar can markedly decrease water evaporation and enhance penetration rates in soils, resulting in improved moisture availability and increased plant biomass, including both root and shoot development in maize (Alghamdi et al., 2024). Biochar generated from coffee pulp enhances soil structure by augmenting porosity and water retention. For example, the application of 5 % coffee biochar decreased water evaporation by 57–66 % and enhanced water retention by 101–130 % in loamy sand soil (Alghamdi et al., 2024). For soil biological properties, the integration of coffee husk biochar into soil has been associated with enhanced microbial biomass and activity. Studies indicate that microbial biomass carbon can substantially increase with elevated applications of coffee biochar, creating a conducive habitat for beneficial microbial populations. This augmentation is ascribed to the porous architecture of biochar, which provides environments for microorganisms and amplifies their metabolic functions (Pouangam Ngalani et al., 2023). Whereas, the fast decomposition of coffee pulp by microbes depletes nutrients such as N during organic matter degradation, resulting in temporary immobilization. Research indicates that microbial fermentation during pulp breakdown modifies nutrient dynamics, diminishing immediate plant availability (Juliastuti et al., 2018). Although, the examination of agricultural by-products, including coffee waste, has lately become significant for enhancing soil conditions worldwide (Sánchez-Reinoso et al., 2023). Nevertheless, research on the impact of local waste derived biochar on the changes of soil characteristic and their application rate in coffee plantation area remains limited. In addition, the absence of a comprehensive investigation of the sustainable coffee pulp biochar production chain in the local region has been encountered.

While biochar derived from agricultural waste shows promise for soil amendment, current research has not yet definitively established optimal applications for specific feedstocks to consistently improve soil quality and agricultural outcomes. Coffee processing residues, particularly coffee pulp, represent a significant agricultural waste stream in highland regions of northern Thailand. These areas present unique waste management challenges due to limited accessibility and transportation infrastructure. The strategic importance of highland areas, often situated in watershed headwaters, underscores the need for effective coffee pulp management. We hypothesized that coffee pulp biochar would serve as an option for recycling local waste and enhance soil quality, hence benefiting the sustainable coffee production chain in the studied area. Moreover, this study utilizes coffee pulp-derived biochar from traditional kiln method. Several methods are currently used to produce biochar, including traditional kiln and modern techniques. Traditional kiln methods offer remarkable accessibility to smallholder farmers and communities with limited resources, providing a more democratized approach to soil amendment compared to industrial systems that require substantial capital investment (Jeffery et al., 2015). While modern gasification systems achieve higher efficiency, traditional techniques leverage locally available materials and indigenous knowledge, creating culturally appropriate solutions that modern technologies often fail to incorporate (Lehmann and Joseph, 2015). The simplicity of traditional kilns provides exceptional resilience against technical failures unlike automated systems that require specialized maintenance, eliminating dependency on complex machinery or external energy sources in remote regions (Cornelissen et al., 2016). Although continuous reactors produce more consistent biochar, traditional methods create valuable employment opportunities and preserve cultural heritage while contributing to climate change mitigation, aspects typically overlooked in efficiency-focused modern approaches (Glaser et al., 2015). Research by Mašek et al. (2013) demonstrates that when properly managed, traditional kilns can produce biochar with beneficial properties comparable to more sophisticated methods but with significantly lower investment costs, making them particularly appropriate for developing regions where modern pyrolysis infrastructure is unattainable. Therefore, the primary objectives of this study were (i) to characterize the physicochemical properties of coffee pulp derived biochar produced from traditional kiln method, (ii) to investigate the efficiency of coffee pulp biochar application for enhancing soil physicochemical and biological properties. This study would demonstrate the potential of biochar derived from local waste in coffee producing regions. The subsequent use of as-made biochar would be mainly focused on the cultivation of coffee cultivation system. The physicochemical and biological properties of the soil were examined to explore the potential practical application rate of biochar in the local farm.

2. Materials and methods

2.1. Site description and experimental design

The experiment was conducted in a greenhouse at Faculty of Agriculture, Chiang Mai University, Thailand (18°76′42″N, 98°93′68″E). The experiment commenced in the cold and dry seasons, spanning from October 2023 to April 2024. The experimental design was a completely randomized design (CRD) comprising 5 treatments with 3 replications. The treatments involved mixing coffee pulp biochar into soil at rates of 0, 2.50, 3.75, 5.00, and 7.50 % of soil weight (5 kg), referred to as B0, B2.5, B3.75, B5, and B7.5, respectively, following the preliminary trial. The soil samples were incubated with different application rates of biochar, with each pot receiving daily irrigation of 50 mL. The pots used in this study were 8 in. in diameter. Three replicates were collected for each soil sample. Soil physicochemical and biological properties were analyzed at 55 days (first day after soil incubation) and 98 days (ends of the experiment). Soil physicochemical properties were assessed in triplicate, while biological properties were analyzed once. The overall research workflow is shown in Fig. 1.

2.2. Raw material for biochar production

Coffee pulp was collected from the Highland Agricultural Research Station, Faculty of Agriculture, Chiang Mai University, Thailand (Fig. 2a). Prior to biochar production, the coffee pulp underwent pretreatment via sun-drying. The desiccated coffee pulp was subsequently stored in plastic bags for further processing into biochar.

2.3. Biochar fabrication

The sun-dried coffee pulp was carbonized through pyrolysis in a traditional kiln to produce coffee pulp biochar (Fig. 2b). The coffee pulp was placed in the chamber, with heat generated beneath it and the lid tightly sealed. The material heated intensely for approximately 30–40 mins and began burning after 60 mins. When it released gases and the flame turned blue without smoke, this indicated complete combustion. The coffee pulp biochar was produced by burning firewood at the bottom of the kiln to initiate the pyrolysis process, which continued for 4 h, followed by a 24 h cooling period. Finally, the coffee pulp biochar was pulverized and filtered through a 2 mm sieve before being used in subsequent studies.

2.4. Coffee pulp biochar characterizations

The surface morphology and element components of the coffee pulp biochar were analyzed by using a High-Resolution Field Emission Scanning Electron Microscope (FE-SEM) with an Energy Dispersive X-Ray detector (Thermo Scientific Apreo S, USA). The pH and EC were analyzed in a suspension of the deionized water-to-biochar solid (1:5 (w/v)) (Rajkovich et al., 2012).

2.5. Soil properties analysis

2.5.1. Soil chemical properties

Soil pH was measured with a Eutech pH 2700 using a ratio of soil with water suspensions (1:2 w/v). Soil electrical conductivity (EC) was measured with a CON 150 EUTECH using a ratio of soil with water suspensions (1:5 w/v). Total N was analyzed using an automated Dumas combustion method (Nitrogen analyzer, LECO 828 Series). Soil exchangeable K, Ca, and Mg were measured using 1 N NH_4OAc (pH 7.0) as the extractant (Thomas, 1982). The exchangeable concentration was analyzed by an atomic absorption spectrophotometer (AAS) (Model contrAA 800/Analytik Jena, Germany). Available P was extracted with Bray No.2 (0.03 N NH_4F + 0.1 N HCl) (Bray and Kurtz, 1945) and measured the absorbance at 882 nm with a Thermo Genesys 20 Spectrophotometer. Soil organic matter (SOM) analysis was measured by following the protocol (Walkley and Black, 1934; Nelson and Sommers, 1982). This is a wet combustion method for analyzing organic carbon in soil. The equation was computed as follows:

$$SOC\ (\%) = SOM\ (\%) \times 0.58 \quad (1)$$

Where SOC is Soil organic matter, SOM is Soil organic matter, and 0.58 is a conversion factor.

2.5.2. Soil biological properties

Microbial populations were determined by using culture media (Egg albumin agar, Rose bengal agar, CMC medium, and Czapek medium). SMR was analyzed by following the protocol (Cheng et al., 2013). 25 g of soil sample was placed into a jar with a sealed lid. Then, the soil moisture was adjusted to achieve 60 % of its water holding capacity. 10 mL of 1.0 M NaOH was added into the jar containing the soil sample for CO_2 trap, where the NaOH captures CO_2 released by microbial respiration.

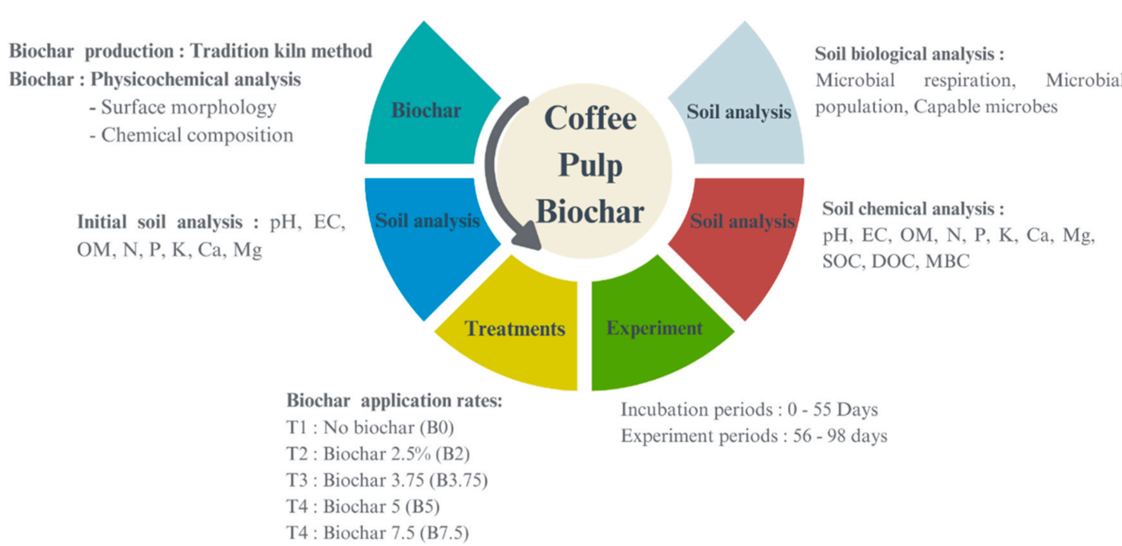


Fig. 1. The research workflow of this study.

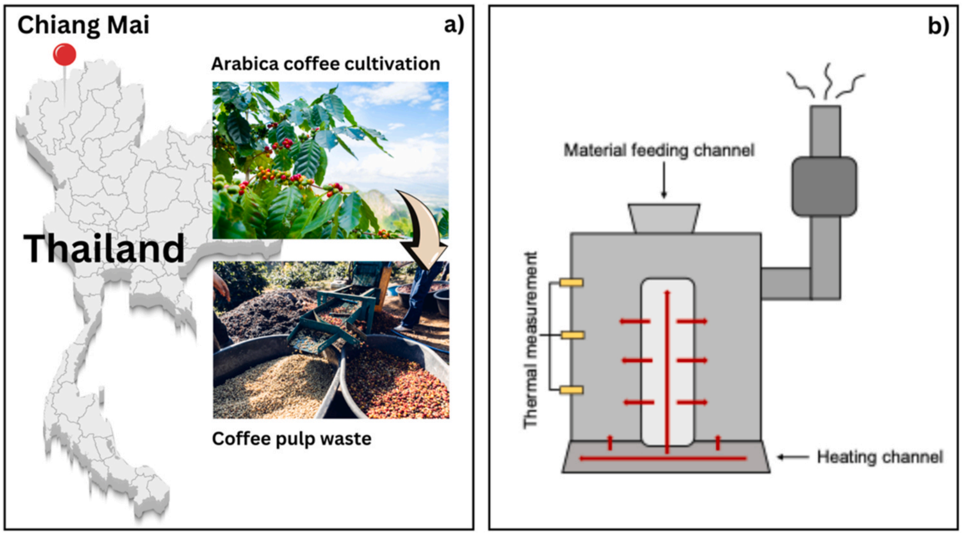


Fig. 2. Location of arabica coffee cultivation (a) and schematic layout of traditional kiln (b).

Then, the soil sample was incubated in the dark for 24 h. After the incubation period, soil sample was dropped with 2 mL of 0.5 M $BaCl_2$ and 5 drops of phenolphthalein indicator then, titrate the solution with 0.1 M HCl procedure, but without adding the soil sample. DOC and MBC were measured following the protocol (Vance et al., 1987; Brookes et al., 1985; Joergensen, 1995; Jenkinson and Powlson, 1976). 10 g of soil sample was placed 2 sets in each sample jar, dividing fumigated and unfumigated ethanol-free chloroform in a fume hood by incubating in the dark for 3 days equally. 10 g of soil sample were placed in two sets of sample jars, one set for fumigation and one for non-fumigation. The fumigation was performed using ethanol-free chloroform in a fume hood, with both sets incubated in the dark for 3 days. Subsequently, each soil sample was extracted with 50 mL of 0.5 M K_2SO_4 and shaken at 250 rpm for 45 mins. The resulting mixture was filtered, and 5 mL of the filtrate was transferred to an Erlenmeyer flask. To this, 5 mL of 0.07 M $K_2Cr_2O_7$ and 10 mL of H_2SO_4 were added. Subsequently, 30 mL of distilled water was added to the cooled solution. The mixture was then titrated with 0.01 M ferrous ammonium sulfate hexahydrate ($(NH_4)_2Fe(SO_4)_2 \cdot 6\,H_2O$) until a visible color change was observed. The DOC and MBC were calculated using the Eqs. (2) and (3), respectively;

$$\text{DOC (µg C/kg soil)} = \text{Cfum} \tag{2}$$

$$\text{MBC (µg C/kg soil)} = (\text{Cfum - Cnon-fum}) / \text{kEC} \tag{3}$$

Where DOC is dissolved organic carbon, MBC is microbial biomass carbon, Cfum is carbon in fumigated sample, Cnon-fum is carbon in non-fumigated sample, kEC is extraction efficiency factor (0.45).

2.6. Statistical analysis

The soil parameters were compared before and after treatment with coffee pulp biochar using one-way ANOVA to determine if there were any statistically significant differences. The least significant difference (LSD) test at a confidence level of 95 % was used to perform the statistical difference among the treatments using Statistix version 10. Correlation analysis was performed by R program. The figures of results were generated through SigmaPlot version 15.

3. Results and discussion

3.1. Biochar characterization

Prior to examining the practical applications of biochar in agricultural soil, a comprehensive characterization analysis of the as-synthesized biochar was conducted. Table 1 presents the results of the coffee pulp biochar characterization. The traditional kiln process used for biochar production yielded approximately 40–45 % of the total dry weight. The coffee pulp biochar exhibited an alkalinity with a pH of 9.77 and an EC of 0.24 dS m^{-1}. The pH of the synthesized coffee pulp biochar was marginally elevated compared to the prior study (Kullachonphuri et al., 2025)., who reported a pH of 9.42. The coffee pulp biochar had a total N content of 0.85 %, slightly lower than that reported in the prior study (Kebede et al., 2023). Additionally, the elemental components K, Ca, and Mg were identified in the coffee pulp biochar, with respective values of 9.69 %, 7.71 %, and 0.72 %.

The characterization of coffee pulp biochar produced in a homemade traditional kiln was assessed by analyzing its surface morphology at three distinct magnifications. Fig. 3a depicts the matrix distribution of pore diameters resembling a honeycomb structure in the coffee pulp biochar samples. The measured pore sizes of the synthesized biochar are 33.90 µm and 25.14 µm at a magnification of 500 ×. However, the presence of a homogeneous pore structure with minute particle cracks was detected after pyrolysis. At a magnification of 1000 ×, the pronounced large pore size with an intricate pore structure of the coffee pulp biochar is evident (Fig. 3b). Upon increasing the magnification to 3000 ×, the existence of a substantial pore size is distinctly apparent (Fig. 3c). As a result of surface morphology analysis, the coffee pulp biochar synthesized from a homemade traditional kiln had pore size distributions. It could serve as an alternative material for boosting soil quality through the adsorption of water or nutrients for sustainable agricultural production.

To determine the important element component in the as-made biochar, an investigation was performed to ascertain the elemental composition of the coffee pulp biochar sample and quantify the elements contained within it (Fig. 4). The analysis revealed that the dominant

Table 1
Characteristics of coffee pulp biochar and soil sample.

Parameters	Coffee pulp biochar	Soil sample
Yield	45 ± 5 %	-
pH	9.77 ± 0.01	6.04 ± 0.07
EC	0.24 ± 0.001 dS m^{-1}	0.36 ± 0.09 dS m^{-1}
OM	17.29 ± 0.05 %	2.96 ± 0.16 %
N_{total}	0.85 ± 0.01 %	0.13 ± 0.01 %
P_{avi}	6.11 ± 0.25 %	174.6 ± 17.90 mg kg^{-1}
K	9.69 ± 0.12 %	208.4 ± 9.79 mg kg^{-1}
Ca	7.71 ± 0.40 %	5181 ± 163.58 mg kg^{-1}
Mg	0.72 ± 0.01 %	160.7 ± 6.58 mg kg^{-1}

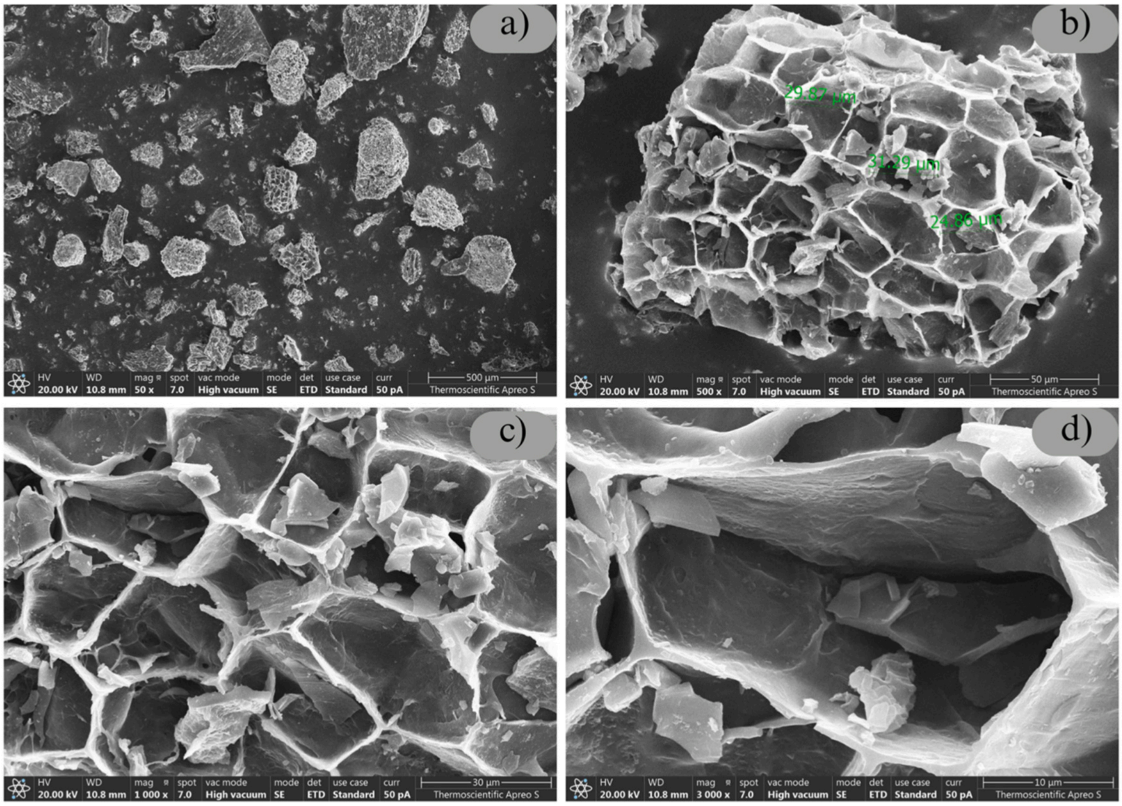
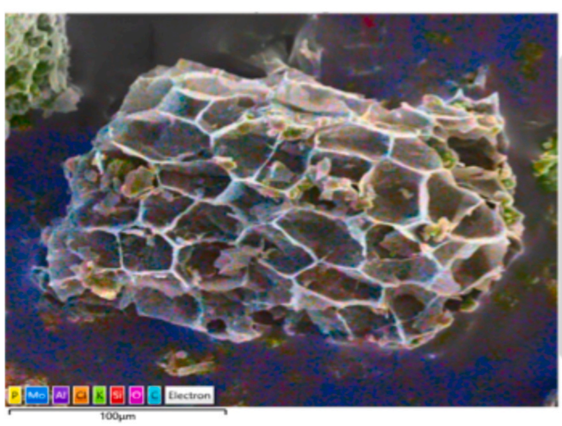


Fig. 3. Surface morphology of synthesized coffee pulp biochar at different magnifications of 50 × (a), 500 × (b), 1000 × (c) and 3000 × (d).



Element	Average weight (%)
C	66.60 ± 6.50
O	19.13 ± 3.40
K	11.63 ± 2.72
Mo	1.43 ± 0.25
P	0.93 ± 0.47
Cl	0.23 ± 0.15
Si	0.07 ± 0.06

Fig. 4. Elemental components of coffee pulp biochar.

element is C, accounting for 66.60 % of the total. This is followed by O, which makes up 19.13 %, and K, which constitutes 11.63 %.

A critical parameter of biochar properties is the presence of surface functional groups. Fig. 4 illustrates the surface functional groups of coffee pulp biochar sample. The results demonstrate the diverse infrared spectra containing in coffee pulp biochar produced by the conventional kiln process. As can be seen from Fig. 5, the functional peaks located at 699.57 cm^{-1} were attributed to the C–H out of plane bending vibration (Mungasavalli et al., 2007). The peak of 827.02 cm^{-1} corresponded to N–H and C–H rocking (Jin and Bai, 2002). The peaks located at 1004.23 cm^{-1} were attributed to the –C–O–C stretching vibration (Philip, 2011). The functional peaks at the wavenumber of 1372.49 cm^{-1} corresponded to the –C–O stretching (Philip, 2011; Kumar et al., 2012). A functional peak appeared at 1581.82 cm^{-1} indicated the N–H bending (Jin and Bai, 2002). The peaks at 2716.74 cm^{-1} and 2920.03 cm^{-1} resulted from the asymmetry of the stretching vibration of symmetrical C–H, primarily originating from aliphatic chemicals, carbohydrates, and alicyclic compounds in organic substances (Chen et al., 2008). Biochar exhibited a peak at a wavenumber of 3865.34 cm^{-1}, corresponding to the stretching vibration of O–H, primarily attributed to the-carboxylic acid, hydroxyl groups, and phenol (Tomczyk et al., 2020).

3.2. Soil properties as affected by coffee pulp biochar application

3.2.1. Soil physicochemical properties

The practical utilization of coffee pulp biochar was assessed by evaluating the alterations in soil characteristics following its application. As shown in Fig. 6(a), the addition of coffee pulp biochar resulted in a significant decrease in available P content from 55 days to 98 days,

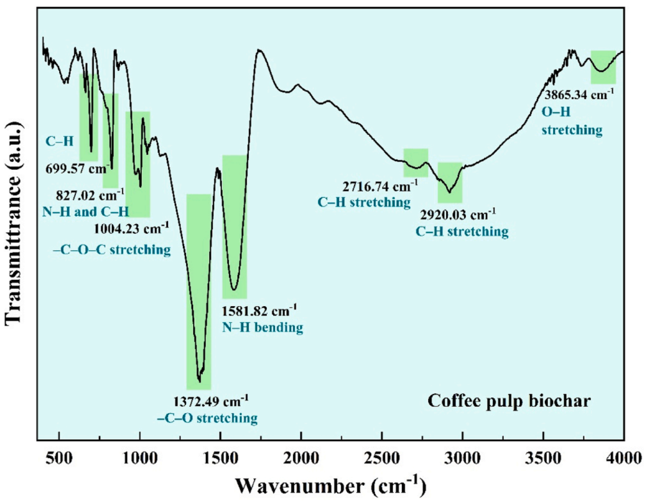


Fig. 5. Fourier transforms infrared spectroscopy (FTIR) spectra of coffee pulp biochar.

which was proportional to the percentage of coffee pulp biochar treatment ($p < 0.05$). In comparison, a reduction in available P content was found across all biochar dose applications following treatment with coffee pulp biochar, even in the absence of biochar addition. Based on the research by Agegnehu et al. (2017), biochar has been found to stimulate microbial growth in soil, potentially immobilizing P and thus reducing available P. For SOM, the incorporation of coffee pulp biochar did not increase a statistically significant difference ($p > 0.05$) in SOM from 55 days to 98 days across treatments with no biochar, 2.5 %, and 5 % biochar dose as shown in Fig. 6(b). However, the treatment with 3.75 % dosage of biochar showed a statistically significant increase ($p < 0.05$) in SOM. In contrast, the application of 7.5 % biochar dosage demonstrated a statistically significant reduction ($p < 0.05$) in SOM following 98 days of biochar treatment. This phenomenon suggests that adding biochar in excessive amounts might lead to SOM saturation, reducing microbial utilization of organic matter due to an excess of organic material. It could also introduce toxins or inhibitors that negatively impact soil microbial activity, thereby reducing organic matter decomposition and accumulation in the soil. Additionally, optimal biochar application can increase SOM and other soil properties, but excessive application may have detrimental effects on SOM and other soil characteristics (Lehmann and Joseph, 2024; Atkinson et al., 2010; Steiner et al., 2007).

The application of biochar into soils significantly influenced the alterations of exchangeable cations due to its alkaline characteristics. The result of soil exchangeable cations analysis is shown from Fig. 7a - c. For exchangeable K, it values increased proportionally with the percentage of coffee pulp biochar treatment. A statistically significant increase was found ($p < 0.05$) in the treatment of coffee pulp biochar, except for the treatment without addition of biochar (control). This can be attributed to the high K content in coffee pulp biochar as shown in EDS analysis result (Fig. 4), where the K was as high as 11.63 %. Consequently, this led to a corresponding increase in soil exchangeable K after coffee pulp biochar application. Similar results representing an increase in soil exchangeable K after the addition of biochar are reported by a previously published article (Adhikari et al., 2024). As a result, exchangeable K is the dominant exchangeable cations in the biochar produced from coffee pulp (Fig. 4). The increase of exchangeable K in the soil-biochar mixture may have resulted from the displacement of soil exchangeable K by the exchangeable K released from biochar. Consequently, coffee pulp biochar is considered a reservoir for significant exchangeable K in soil. For soil exchangeable Ca, the results were only statistically significantly ($p < 0.05$) increase in the dose of biochar 5 % (Fig. 7b). In treatments with 2.5 %, 3.75 %, and 7 % biochar doses, the soil exchangeable Ca exhibited a modest increase, but not statistically significant changes were noted ($p > 0.05$). However, there was not statistically significant decrease in soil exchangeable Ca of control treatment. As shown in Fig. 7c, the soil exchangeable Mg values decreased significantly ($p < 0.05$) in all biochar treatment and control. However, a statistically significant decrease ($p < 0.05$) was observed, except for the treatment with 2.5 % biochar dosage. Alkharabsheh et al. (2021) indicates that biochar can effectively absorb Ca and Mg due to its high CEC. This result presents in a decrease of exchangeable Ca and exchangeable Mg in the soil after biochar treatment. The incorporation of biochar with low Ca and Mg content (as indicated in Table 1) or the adsorption of Ca and Mg from the soil may be inadequate to offset the Ca and Mg absorbed by the biochar. According to Laird et al. (2010), biochar has been shown to increase CEC in soil, thereby enhancing the levels of exchangeable K. However, concurrently, it may decrease exchangeable due to ion competition and changes in soil pH. Biochar with an elevated pH (e.g., 8.76) has demonstrated the capacity to raise soil pH in acidic soils by 0.5–1 unit. The increase in pH may lead to the

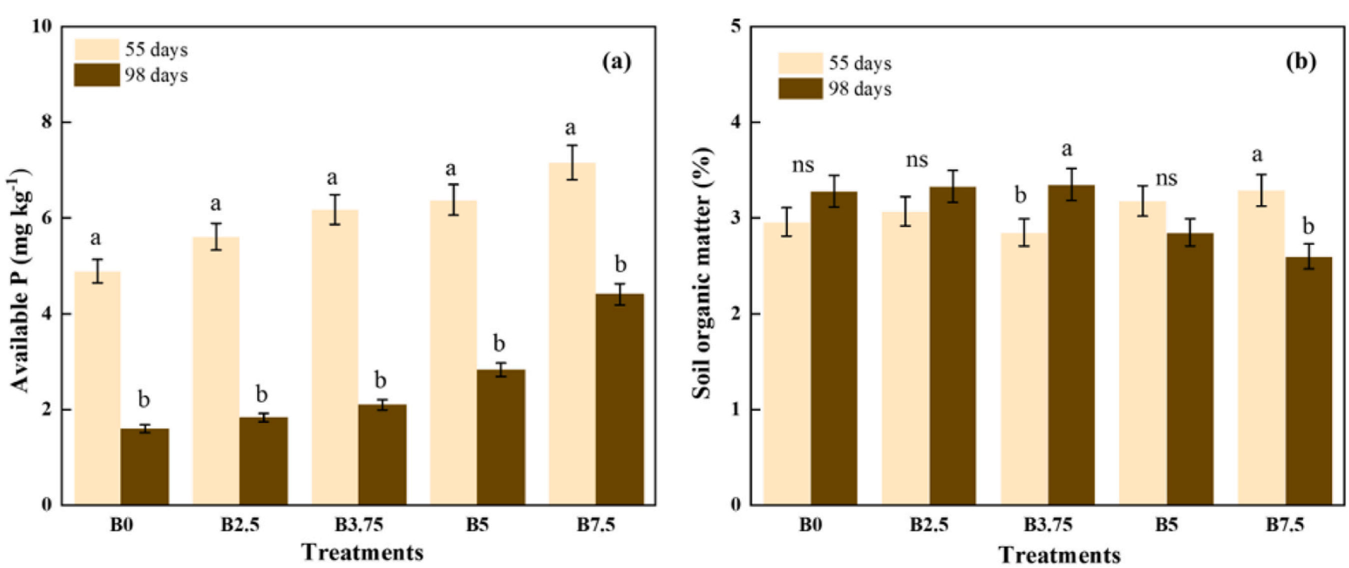


Fig. 6. Soil available P (a) and soil organic matter (b) after treated with different dosages of coffee pulp biochar. Distinct letters indicate statistically significant differences ($p < 0.05$).

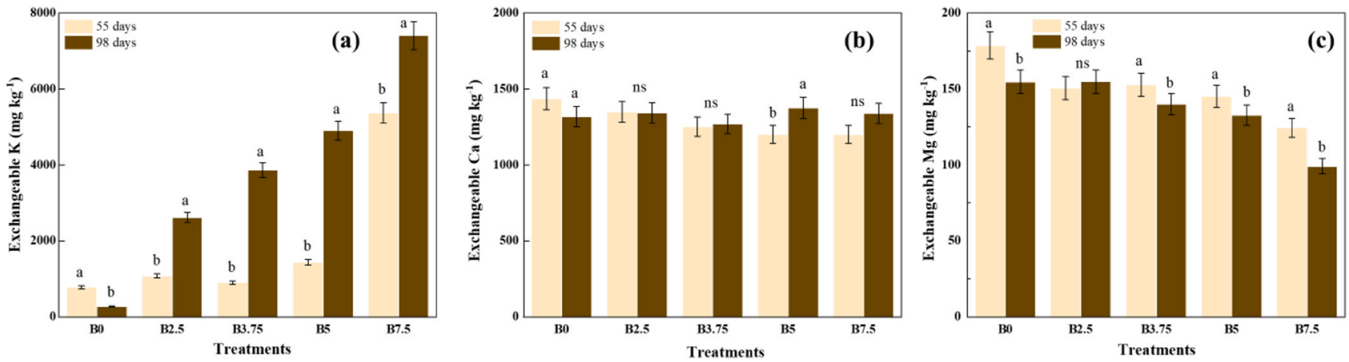


Fig. 7. Soil exchangeable K (a), exchangeable Ca (b), and exchangeable Mg (c) after treated with different dosages of coffee pulp biochar. Distinct letters indicate statistically significant differences ($p < 0.05$).

precipitation of K⁺ in less soluble forms, hence diminishing its availability for exchange (Anderson et al., 2011).

Fig. 8a illustrates the soil pH results after coffee pulp biochar treatment. The soil pH consistently elevated following the dosage of coffee pulp biochar application. The most significant rise in soil pH following the application of coffee pulp biochar was noted at a concentration of 7.5 % biochar treatment. According to previous study of Jalalabadi (2021), the finding has shown that biochar production at high temperatures results in alkaline substances such as calcium carbonate ($CaCO_3$) and potassium carbonate (K_2CO_3), which are major factors contributing to soil pH increase after biochar application. A similar trend of increase was observed in the result of soil EC after biochar treatment (Fig. 8b).

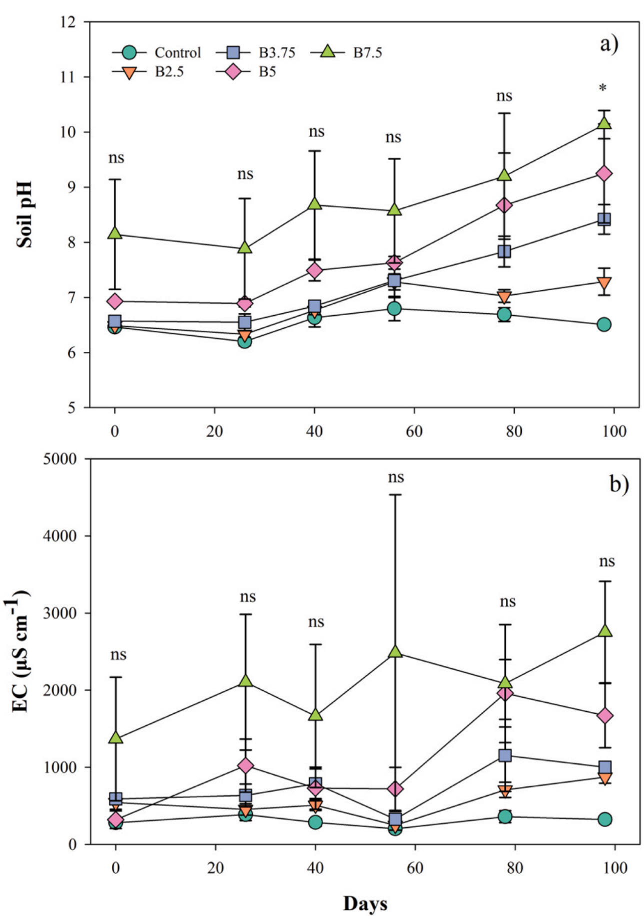


Fig. 8. Soil pH (a) and soil EC (b) after incubation with different dosage of coffee pulp biochar. **Note:** * = Significant difference at $p < 0.05$, ns = Non-statistical significant difference at $p < 0.05$. Error bars = Standard Error.

The tendency of increased soil EC was seen with the duration of coffee pulp biochar treatment. The maximum soil EC was also observed in the treatment with a biochar dosage of 7.5 %. Xu et al. (2017) demonstrate the impact of biochar derived from diverse sources, including coffee pulp and shells, on soil EC. The application of biochar was found to increase soil EC, primarily attributed to the release of ions such as Ca^{2+}, Mg^{2+}, and K^{+} from the biochar into the soil solution.

3.2.2. *Soil biological properties*

The biological qualities of soil undergo fast changes relative to its physical and chemical properties. Therefore, to illustrate the ability of coffee pulp biochar as the soil amendment, the soil biological properties were analyzed after biochar treatment. As shown in Fig. 9a, after treatment with coffee pulp biochar, SMR exhibited statistically significantly difference among treatments ($p < 0.05$). The treatment with 7.5 % coffee pulp biochar addition in soil demonstrated the highest increase in SMR compared to other treatments. Also, coffee pulp biochar resulted in statistically significant differences ($p < 0.05$) increase in DOC (Fig. 9b). However, the observed values for MBC exhibited an inverse relationship (Fig. 9c). The treatment without the addition of coffee pulp biochar was substantially higher than the biochar treatment. The 7.5 % biochar application dosage was the lowest, although it was not significantly different from the 5 % dosage. As aforementioned results, it is evident that SMR and DOC increased when increasing the percentages of coffee pulp biochar application. Conversely, MBC decreases with increasing dosage of biochar application. According to the studies of Lehmann et al. (2011) and Nguyen et al. (2013), SMR is an indicator of microbial respiratory activity in the soil, which typically increases when additional nutrients are introduced into the soil, such as in the case of coffee pulp biochar application. Coffee pulp biochar may serve as a source of organic carbon for microbial metabolism. While the increase in DOC in the soil results in higher SMR, as microorganisms can utilize this DOC as an energy source for their respiratory processes. On the other hand, MBC represents the amount of carbon incorporated into microbial cells in the soil. The rise in SMR may enhance carbon metabolism in the soil, potentially resulting in a reduction in MBC, as the metabolized carbon may not promptly facilitate the production of new MBC. This could also indicate a reduction in the microbial population in the soil during periods of increased metabolic activity.

Fig. 10a clearly indicates that treatment with coffee pulp biochar correlates with an increase in bacterial and actinomycete populations except for treatment with 7.5 % biochar of soil weight. While fungi in the biochar treatments decreased as compared to control treatment. However, the increase of fungi was evidenced in the 7.5 % of biochar dosage. The augmented bacteria and fungi may be stimulated by a biochar-mediated increase in pH that alleviates acid stress in bacteria. The co-occurrence network demonstrated that the addition of biochar enhanced bacterial competition against fungi, resulting in reduced aggregation and stability (Chen et al., 2021). According to Lehmann and

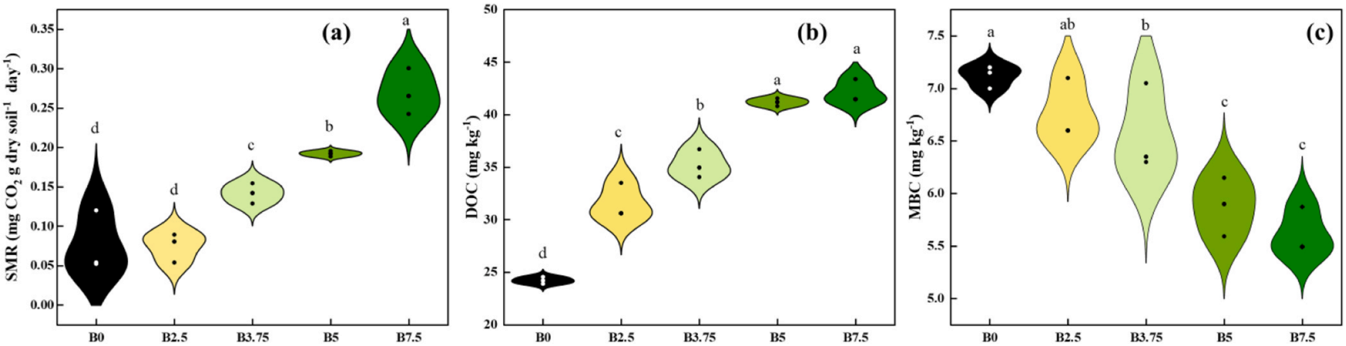


Fig. 9. Levels of Soil Microbial Respiration (SMR) (a), Dissolved Organic Carbon (DOC) (b), and Microbial biomass carbon (MBC) (c) under treated with coffee pulp biochar for 98 days. Distinct letters indicate statistically significant differences ($p < 0.05$).

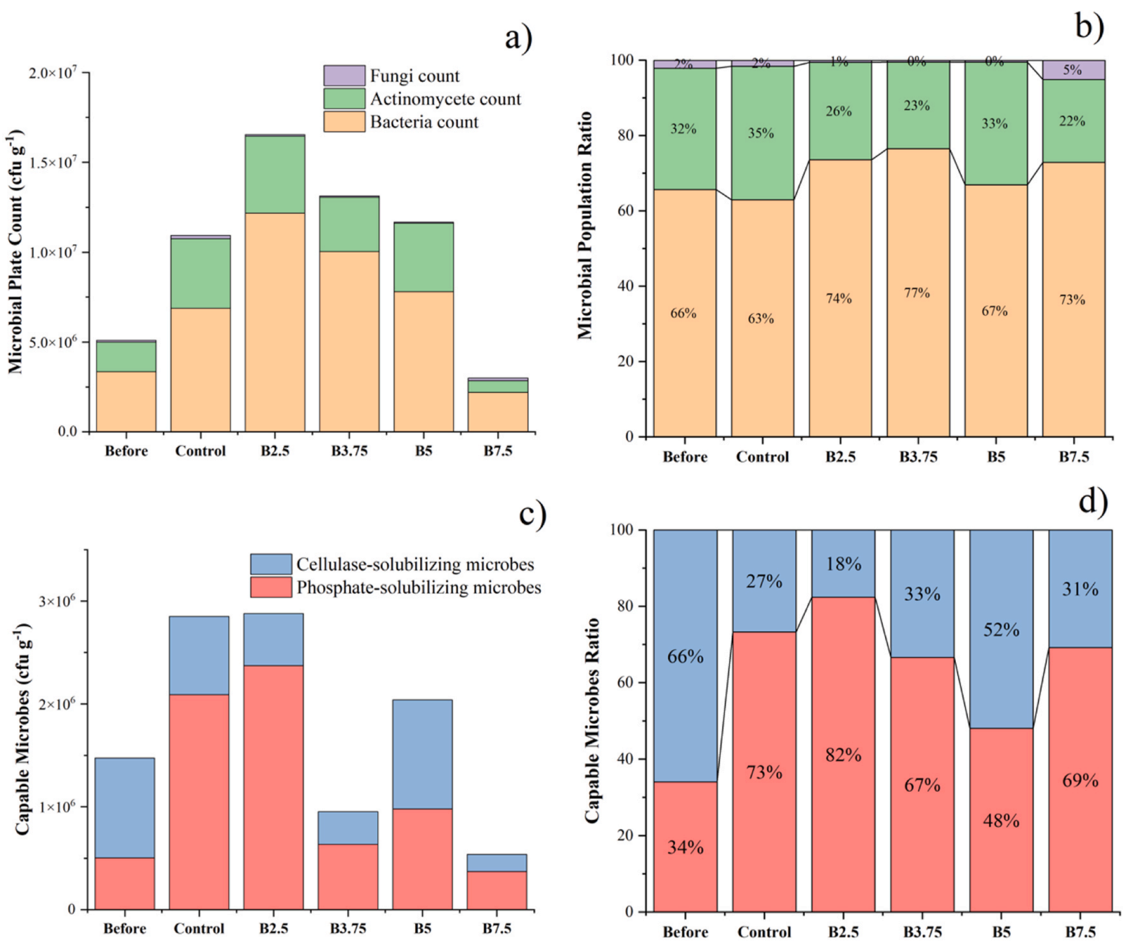


Fig. 10. The results of microbial population (a), Microbial population ratio (b), Capable microbes (c) and Capable microbes ratio (d), under different coffee pulp biochar application rates.

Joseph (2024), biochar significantly influences the distribution and quantity of soil microorganisms, particularly increasing bacteria and actinomycetes, while decreasing fungi. This is due to biochar's chemical and physical properties that can alter soil environmental conditions. Cellulases are crucial for the breakdown of organic materials and the cycle of nitrogen in soil environments (Ma et al., 2024). This investigation highlighted the increase of cellulase-producing microbes after as-made biochar treatment. The glucose generated from cellulose decomposition acts as a carbon source for soil microbes. These microorganisms mineralize organic nitrogen molecules (e.g., proteins) into inorganic forms such as ammonium (NH_4^+), which can then be reduced to nitrate (NO_3^-) via nitrification. This mechanism renders nitrogen accessible for plant absorption, hence enhancing plant growth and soil fertility (Choi et al., 2018). There is evidence for an increase in the number of cellulase-producing microorganisms in the biochar treatment of 2.5 % and 5 % (Fig. 10c). An increase in phosphate-solubilizing microorganisms was also found in without biochar treatment as compared to original soil sample. The application of 5 % biochar resulted in a singular enhancement in phosphate-solubilizing bacteria relative to the original soil sample among the treatments.

3.2.3. Correlation between soil physicochemical and biological properties

The correlation analysis between soil properties after coffee pulp biochar treatment is tabulated (Fig. 11). Exchangeable K and available P were both positively associated with SMR and DOC. The strong association is evidenced in the relationship between exchangeable K and DOC (r = 0.95). Consequently, SMR exhibits a positive correlation with DOC (r = 0.84). The coffee pulp biochar contains a high amount of exchangeable K (Table 1 and Fig. 3) resulting in the high value of the SMR and DOC. According to the soil properties analysis results, the maximum exchangeable K was observed with a 7.5 % biochar application. A similar pattern was noted for SMR and DOC, both of which were significantly highest in the 7.5 % condition. The MBC exhibits a robust negative connection with exchangeable K (r = -0.87). While the exchangeable Mg displayed an inverse link with the SMR and DOC. However, exchangeable Mg exhibits a favorable correlation with the MBC (r = 0.73). Furthermore, SOM exhibited a favorable connection with exchangeable Mg (r = 0.72) and MBC (r = 0.73).

4. Conclusions

Coffee pulp biochar produced from traditional kiln method exposed a unique property which contains the high amount of exchangeable K, various surface functional groups and evident pore structures. The incorporation of coffee pulp biochar dramatically altered soil physicochemical and biological characteristics during a short incubation period of 55 and 98 days. High containing exchangeable K in coffee pulp biochar considerably elevated soil exchangeable K, correlating with biochar application rates ranging from 0 % to 7.50 %. While, the substantial increase in SOM was seen solely at 3.75 % and 7.50 % biochar treatment rates. For the soil biological analysis, dosages of biochar at 2.50 %, 3.75 %, and 5 % significantly enhanced the populations of bacteria and actinomycetes. However, when the dose was increased to 7.5 %, the populations of bacteria, actinomycetes, and fungus dropped to levels lower than those in the untreated biochar. Similarly, excessive addition of biochar at 7.5 % led to a reduction in cellulase-producing microorganisms and phosphate-solubilizing microorganisms. The connection distinctly illustrates the positive association of soil exchangeable potassium with the soil biological parameters of soil microbial respiration and dissolved organic carbon at 0.91 and 0.95, respectively. This suggests that moderate levels of coffee pulp biochar application can beneficially impact soil microbial populations and enzyme activities, while higher levels may have adverse effects on certain beneficial microorganisms. This study contributes to the comprehension of waste management in coffee production and presents an examination of soil parameters following treatment with coffee pulp biochar, facilitating future research planning. Nonetheless, the lasting effects of biochar on soil chemical and microbiological characteristics may differ among distinct biochar feedstocks. Consequently, further investigations on diverse biochar feedstocks are necessary to evaluate the effects of biochar on soils in contemporary situations. Also, an assessment of the capacity of coffee pulp biochar to absorb carbon and enhance soil resistance to climate change, especially in areas susceptible to drought or excessive rainfall, is necessary.

CRediT authorship contribution statement

Nuttapon Khongdee: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yaoliang Chen:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Piyaphad Ninlaphong:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sasiprapa Kullachonphuri:** Writing – review & editing, Formal analysis, Data curation. **Kesinee Iamsaard:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Investigation, Formal analysis, Conceptualization. **Yupa Chromkaew:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Formal analysis, Conceptualization. **Phonlawat Soilueang:** Writing – review & editing,

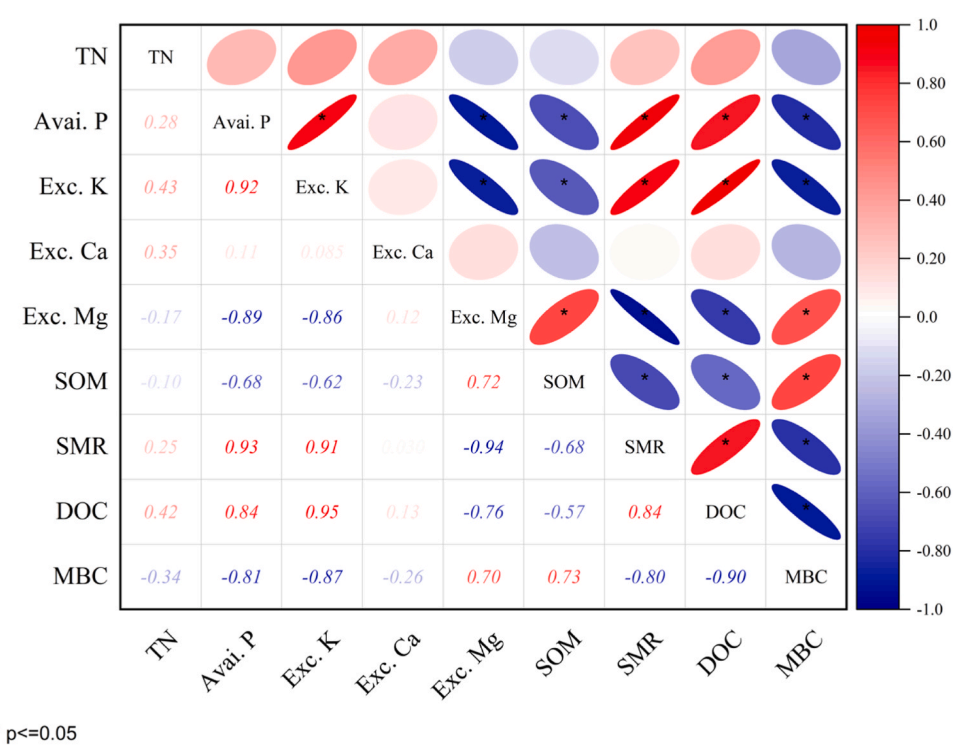


Fig. 11. Pearson's correlation matrix of soil properties after coffee pulp biochar treatment for 98 days at significant value of $p \leq 0.05$. More circular shapes indicate weaker correlations. A curve from white to dark blue signifies positive correlations. An oval shape from white to dark red indicates negative correlations. Dark blue or red represent robust correlations.

Formal analysis, Data curation. **Toungporn Uttarotai:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Conceptualization. **Metinee Nakdee:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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