HAYATI
Journal of Biosciences
Vol. 33 No. 2, March 2026 394-403
DOI:10.4308/hjb.33.2.394-403
ISSN: 1978-3019
EISSN: 2086-4094

Research Article

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Termites as Soil Engineers: A Study on Organic Carbon and Nutrient Dynamics using Baiting Techniques in Tropical Forest Ecosystem

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ARTICLE INFO

Article history:
Received February 3, 2025
Received in revised form June 22, 2025
Accepted August 17, 2025
Available Online November 19, 2025

KEYWORDS:
Termites Activity,
Soil fertility,
Macrotermes,
Microtermes,
Schedorhinotermes,
Diversity index

ABSTRACT

This study explores how termite activity affects soil chemistry, those are Soil Organic Matter (SOC) and nutrient dynamics in pine and mahagony forest of varying ages in the Bromo Forest, Indonesia. Termite activity was assessed using wooden poles placed in PVC pipes as bait, which also served for soil sampling. The results showed significant differences in SOC and total NPK levels among different pole damage classes in each forest. The highest values were observed in pole damage class 4. Termite-influenced soil, especially those affected by the genera *Macrotermes* sp., *Microtermes* sp., and *Schedorhinotermes* sp., showed the highest concentrations of SOC and NPK (4.97%, 0.51%, 15.42 mg/100 g, and 45.9 mg/100 g, respectively). The termite diversity index showed moderate diversity in all pine forests and low diversity in mahogany forests. The termite diversity index indicated moderate diversity in pine forests and low diversity in mahogany forests, likely influenced by bait type. These results demonstrate that termite activity significantly enhances soil nutrient content and can be used as an indicator of soil fertility status in tropical forest ecosystems.

1. Introduction

Termites have been widely recognized as pests due to their destructive impact on wood, such as in plantation areas. Studies reported that termites have been identified as significant pests in various agricultural settings, including oil palm plantations (Jalaludin *et al*. 2018), teak plantations (Fajar *et al*. 2021), and multiple crops such as corn (Loko *et al*. 2024), rice, and sugarcane (Lefèvre 2011) that generate substantial economic losses. However, despite their reputation as pests, termites also play an essential role as bioindicators of environmental quality due to their role as weathering agents in tropical regions (Issoufou *et al*. 2019; Jouquet *et al*. 2002). Their activities contribute to nutrient production and cycling, which can be beneficial for ecosystem functioning (Chhotani and Bose 2024).

Termites build biogenic structures such as mounds, tunnels, and layers in the soil, which alter

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soil properties such as increased porosity, improved aeration, soil drainage, increased soil aggregate stability, and increased nutrient availability (Jouquet *et al*. 2006; Jouqueta *et al*. 2011). Research in the Sabana region has demonstrated the potential of termite mounds to improve soil quality by acting as nutrient centers (López-Hernández 2023). This potential has led smallholder farmers in South Africa to use termite mounds as an alternative to NPK fertilizer (Chisanga *et al*. 2020). This is demonstrated by the study of Mokossesse *et al*. (2012), which reports that the application of termite mound soil (*Cubitermes* sp.) as fertilizer can increase maize yield by up to 53.4% (from 1.87 t/ha to 2.89 t/ha in 2007) and 44.7% (from 2.17 t/ha to 3.17 t/ha in 2008) when 1 kg of Termite-influenced soil is applied per plant. Other research conducted by Sathiya *et al*. (2018), on corn plants also showed that the application of fertiliser mixed with termite-influenced soil produced higher values, with the highest values produced by the treatment of inorganic fertiliser combined with termite-influenced soil, resulting in the highest plant height of 78.32 cm, leaf area of 159.2 cm^2, dry matter production of 123.67 g, and chlorophyll content of 2.1 mg/g. Meanwhile, the control treatment yielded the lowest growth, with plant height of only 61.25 cm, leaf area of 140.1 cm^2, dry matter production of 118.47 g, and chlorophyll content of 0.95 mg/g.

Previous studies have shown the importance of termite ecology in improving soil fertility. Therefore, identifying the dominant termite genera in various regions is essential for understanding their potential role in sustainable agriculture. In Indonesia, commonly found subterranean termite genera include *Macrotermes* (Ferbiyanto *et al*. 2015), *Microtermes* (Arinana *et al*. 2022), *Odontotermes* and *Schedorhinotermes* (Arif *et al*. 2021).

The contribution of termites in improving soil properties is intrinsically linked to their habitat conditions, particularly in forests. Various types of land affect environmental conditions and soil fertility, especially the topsoil layer, as termites tend to prefer soil dominated by clay, sufficient rainfall, and optimum conditions with high humidity, which in turn affects the diversity and density of the termite population (Augustoa *et al*. 2007). A study in Malawi revealed that stand conditions directly impact the landscape distribution of termites (Nyirenda *et al*. 2019). Environmental factors, including stand type, contribute to termite population diversity. This is related to litter condition, as termites prefer litter with high levels of secondary compounds, such as phenolics and tannins, which promote litter decomposition (de Jonge *et al*. 2024). Additionally, termite population density is influenced by their preferences for specific stand types. For instance, research has shown that termites exhibit a preference for pine wood (Waller *et al*. 1990). Termites prefer pine wood due to the presence of dehydroabietic acid, a diterpenoid that serves as a chemical attractant during wood decay (Mitaka *et al*. 2024). Rubberwood, oil palm (Arinana *et al*. 2022), and eucalyptus (Sebayang and Susanti 2024) are also highly susceptible to termite consumption.

This study was conducted to investigate the level of termite diversity in pine and mahogany forests of different ages in the Alas Bromo Educational Forest, as these two species are dominant in the area and reflect the actual forest conditions. The selection of different stands also aimed to observe the response of termites to varying types of wood. Differences in stand age were also used to show the actual conditions of the location. The objectives of this study were to analyse termite activity levels using termite trap posts in pipes, determine soil organic carbon (SOC) and NPK nutrient content at each termite activity level based on post damage class, and compare them with soil formed by termites in pipes.

2. Materials and Methods

2.1. Study Site

This study was conducted in pine and mahogany forests in the Alas Bromo Educational Forest Area, Karanganyar District, Karanganyar Regency, Central Java, Indonesia. The research period ran from July to December 2024, with bait stakes installed in July, when the average rainfall for that month was 1.50 mm^2 and the mean daily temperature was approximately 27°C. Soil analysis was conducted at the Soil Chemistry and Fertility Laboratory, Faculty of Agriculture, Sebelas Maret University. The research location was selected in slope class 2 (8-15%). This study used a descriptive exploratory method with a purposive sampling approach, focusing on forests suspected of having high termite activity, as indicated by signs of termite attacks on trees, evidence of bioturbation caused by termites, and the presence of decaying wood (Table 1).

The presence of termite activity was identified by installing wooden baits at each location. The wooden bait method was modified from Rachmadiyanto *et al*. (2023)

and adapted to field conditions. The species of wood used as bait was matched to the dominant tree species at each site, with dimensions of 3 cm × 3 cm (width) × 20 cm (length). The wood used is unprocessed. The baited area measured 25 m × 25 m, and four replicate plots were installed in each region. Additionally, in contrast to the previous method, the wooden baits were placed inside a PVC pipe 25 cm in length and 5 cm in diameter. The pipe was perforated along its side for 20 cm to allow termite entry and colony formation (Figure 1). The baits were left in the field for 2 weeks, after which their condition was assessed to determine damage class (Table 2). Termite samples were also collected for genus identification. The use of wooden baits matching the dominant tree species was intended to reflect the actual conditions of the study site.

Table 1. Location of termite bait stakes in the Alas Bromo Educational Forest

Location	Stand Type	GPS Location
Location 1	Pine 1973	7° 35′ 5.56″ S; 110° 59′ 47.25″ E
Location 2	Pine 1994	7° 35′ 33.72″ S; 111° 0′ 36.38″ E
Location 3	Pine 2001	7° 35′ 30.17″ S; 111° 0′ 26.57″ E
Location 4	Pine 2016	7° 34′ 59.58″ S; 110° 59′ 45.21″ E
Location 5	Mahogany 1949	7° 35′ 7.34″ S; 110° 59′ 41.35″ E
Location 6	Mahogany 1973	7° 34′ 57.50″ S; 110° 59′ 40.98″ E

2.2. Soil Chemical Properties

Three types of soil samples were collected: 1. Composite soil samples from each block before pole installation (control), taken at a depth of 0-20 cm. 2. Stake soil, which is soil collected around the stake at a depth of 0-20 cm and collected based on the damage class of the stake in each stand (collected two weeks after stake installation). 3. Termite-influenced soil, which is soil formed by termites in the installed pipes (Figure 3). Each soil sample was air-dried at room temperature, gently disaggregated, and passed through a <1 mm sieve before analysis. Soil Organic Carbon was determined using the Walkley and Black wet oxidation method (Walkley & Black), Total Nitrogen using the Kjeldahl digestion-distillation method, and Total Phosphorus and Total Potassium using the HCl extraction method.

2.3. Statistical Analysis

One-way ANOVA was used to determine the effects of damage class on soil chemical properties in each stand, Termite-influenced soil, and control. Duncan's Multiple Range Test (DMRT) was subsequently applied at a 95% confidence level ($p<0.05$) to compare the means of different groups and identify which were significantly different from each other in the context of this study.

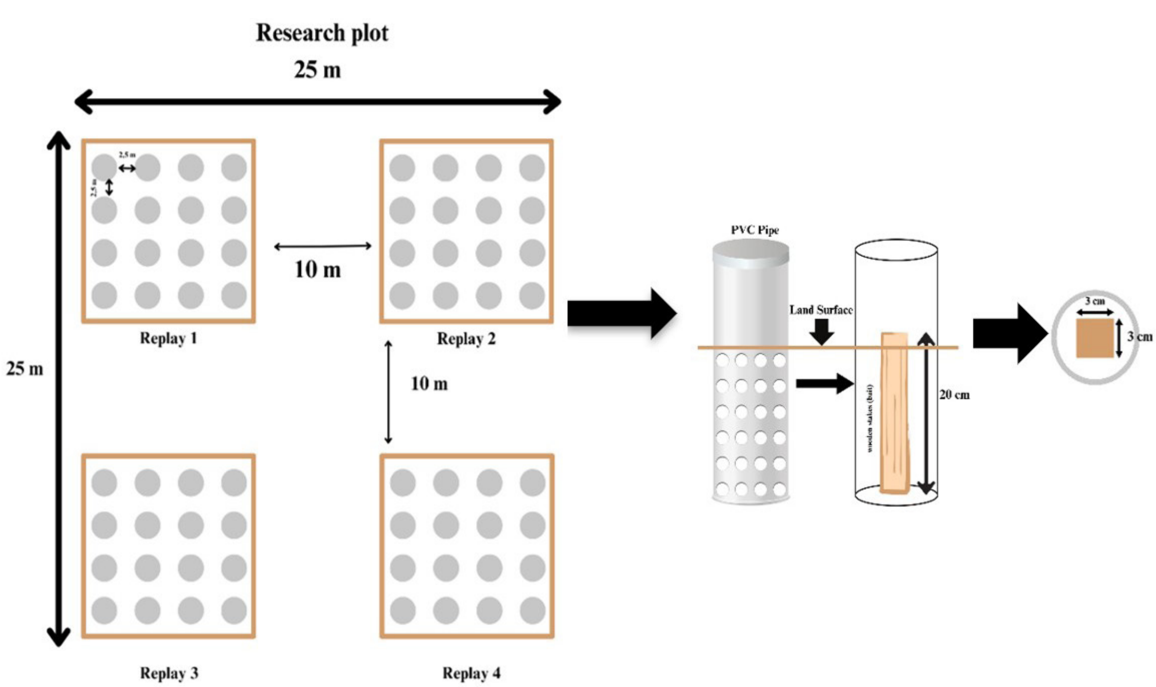

Figure 1. Design of the stake installation for termite activity assessment (Modified from Rachmadiyanto *et al*. 2023)

Table 2. Classes and criteria of damage to wooden stakes used to assess termite activity

Damage class	Damage level	Damage criteria for stakes
Class 0	Undamaged	No termites or attack marks were found
Class 1	Minor Damage	There were traces of termite infestation on the stake, but no termites were found.
Class 2	Moderately damaged	There is damage to the stake due to termite attacks and deeper attack holes.
Class 3	Damaged	There was significant damage to the wooden stake, and the attack was quite severe.
Class 4	Severely damaged	In this class, very severe damage to wooden stakes (deep and thorough damage) or the state of the stakes has disappeared, indicating that termite infestation activity is usually no longer active.

Reference: (Rachmadiyanto *et al.* 2023)

Termite diversity in each stand was measured using the Shannon-Wiener Diversity Index Formula (Spellerberg and Fedor 2003; Soetignya *et al*. 2021). Termite diversity was calculated by identifying and counting the number of genera found in each bait stake within the stand. The total number of genera per stand was then used to calculate the Shannon-Wiener Diversity Index.

$$H' = -\sum_{i=1}^{n} pi \ \text{In} \ pi$$

Description: H': Shannon-Wiener diversity index; pi: the proportion of species i to the total species; ln: natural logarithms; ni: the number of individuals of species I; N: the total number of all species. The criteria for interpreting the Shannon-Wiener diversity index (H') are: H'< 1 = low diversity; 1 < H' < 3 = medium diversity, and H' > 3 = High diversity.

3. Results

3.1. Termite Diversity Index on Each Stand

Termite genera identified in this study include: *Macrotermes* sp., *Microtermes* sp., *Schedorhinotermes* sp., and *Odontotermes* sp. (Figure 2). The termite diversity index varied across the stands. Pine stands exhibited a medium diversity index, with the highest value observed in the 2001 pine stand (H' = 2.52). In contrast, the 1973 and 1949 mahogany stands showed low diversity indices (H' = 0.56 and H' = 0.96, respectively) (Table 3).

3.2. Soil Organic Carbon (SOC) and Nutrient Content (NPK) Based on The Damage Classification of The Stake on Each Stand

The damage class of the bait stakes is categorised into five classes (classes 0-4), with the damage class classification based on the criteria in Table 2. The level of damage to the stakes reflects the level of termite activity, where the higher the damage class, the higher the termite activity. A higher damage class indicates greater termite activity at that location. Control soil represents the initial soil conditions before pile installation, taken as a composite sample at several points and collected at each observation location. Significant differences in SOC levels and total soil NPK were observed across the stake damage classes in each stand (Table 4).

Table 4 shows that the SOC and NPK values of total soil in the 1994 pine stand were the highest values produced in soils with marker damage class 4, namely (2.49%, 0.40%, 4.84 mg/100g, and 32.32 mg/100g). The same trend was shown by the 1973 pine stands (1.48%, 0.42%, 7.63 mg/100g, and 28.88 mg/100g), 2001 pine (1.81%, 0.41%, 7.22 mg/100g, and 45.58 mg/100g) and 2016 pine (1.70%, 0.39%, 12.91 mg/100g, and 20.49 mg/100g). The 1973 Mahogany Stand produced the highest values for SOC and total soil NPK in damage class 4 (2.54%, 0.43%, 12.15 mg/100g, and 34.25 mg/100g). In contrast to other stands, on the 1949 mahogany stands, no damage classes 3 and 4 were found, so soil analysis was only carried out up to damage class 2. The highest values of SOC and total NPK of soil were produced by damage class 2 (3.40%, 0.53%, 4.53 mg/100g, and 60.87 mg/100g). SOC and NPK contents increased with termite activity, with the highest concentrations observed in damage class 4 and the lowest in class 0 and control soils.

3.3. Differences in SOC Levels and NPK Nutrients in Soil Based on The Class of Stake Damage and Termite Genus

In this study, the pipe method not only assessed termite activity but also allowed the collection of termite-processed soil, providing insight into nutrient dynamics. Visually, the termite-formed soil collected in this study was soil found in pipes. This soil was the result of termite

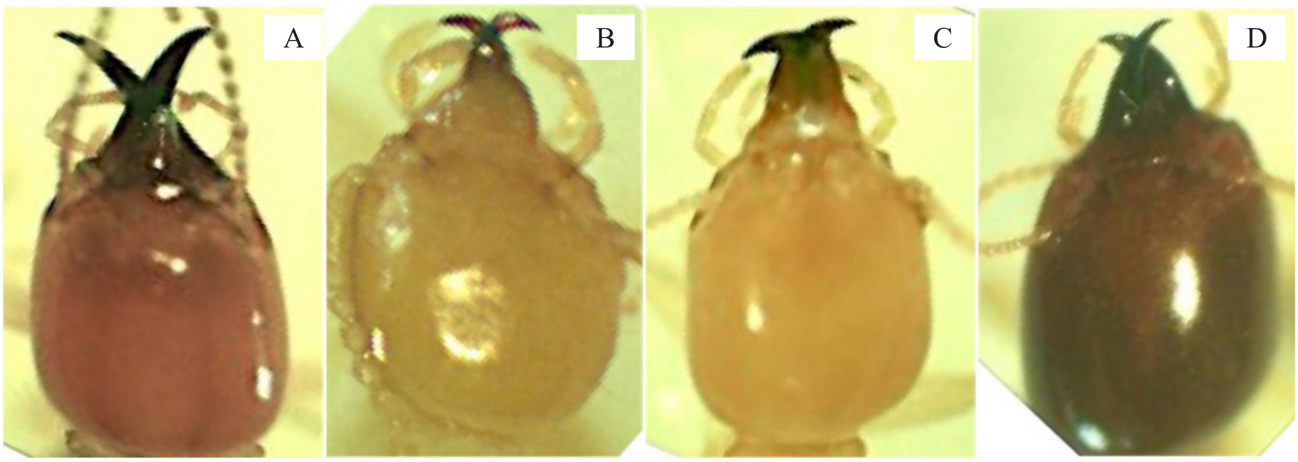

Figure 2. Termite genera identified in the Alas Bromo Educational Forest: (A) *Macrotermes* sp. (Minor), (B) *Microtermes* sp., (C) *Schedorhinotermes* sp., (D) *Odontotermes* sp.

Table 3. Termite diversity index (H') in pine and mahogany stands of the Alas Bromo educational forest

Stand type	H'	Criteria diversity index
Pine 1994	1.22	Medium
Pine 1973	2.37	Medium
Pine 2001	2.52	Medium
Pine 2016	2.44	Medium
Mahogany 1973	0.56	Low
Mahogany 1949	0.96	Low

activity (Figure 3). Significant differences in SOC and total NPK levels were observed between soils formed by different termite genera, soils collected from around the stakes with varying damage classes, soils from different stand types, and control soils.

The highest SOC content (4.97%) was found in soil associated with a combination of three termite genera: *Microtermes* sp., *Macrotermes* sp., and *Schedorhinotermes* sp. These genera coexist in a single bait station inside a pipe (Figure 4). This value was significantly different from other soils. The next highest SOC content was observed in soil associated with *Macrotermes* sp. and *Schedorhinotermes* sp. (2.59%), followed by Macrotermes sp. (2.14%) and *Microtermes* sp. (2.05%).

The NPK nutrient content followed a similar trend to SOC (Figure 4). The high nutrient content in soils associated with this termite genus is likely due to synergistic decomposition strategies, whereby each genus has different enzymes and methods of breaking down organic matter, thereby contributing uniquely to nutrient mobilisation. The highest NPK content was found in soil associated with *Microtermes* sp., *Macrotermes* sp., and *Schedorhinotermes* sp., with values of 0.51%, 15.42 mg/100g, and 45.9 mg/100g for N, P, and K, respectively. These values were significantly different from other soils. The lowest N content (0.22%) was observed in soil from stake damage class 0, while the lowest P and K content (4.65 mg/100g and 21.79 mg/100g, respectively) was found in control soils.

4. Discussion

The observed differences in the diversity index can be attributed to the variation in the bait used. Different types of wood have various levels of resistance to termite damage (Kalleshwaraswamy *et al*. 2022). In this study, each stand was baited with stakes made of the corresponding wood type. Pine is one of the preferred types of wood for termites and is frequently used as bait due to its palatability (Waller *et al*. 1990). This preference may be influenced by its lower density and softer structure, which makes it easier for termites to consume (Arinana *et al*. 2022). The presence of dehydroabietic acid, a diterpenoid that attracts termites during wood decay (Mitaka *et al*. 2024). In contrast, mahogany is less preferred and less attractive to termites (Ramos and Rojas 2001), and it is known for its resistance to termite attacks (Morales-Ramos and Rojas 2001).

The critical role of termites in changing soil structure through biogenic buildings, such as mounds and galleries (Jouquet *et al*. 2016). However, such structural changes generally reflect long-term termite activity. In contrast, this study, conducted over two weeks, reflects short-term indicators of termite presence and early-stage soil interaction. Contributes to the enrichment of organic carbon as well as other essential nutrients, and the enrichment of these nutrients supports the improvement

Table 4. Soil organic carbon (SOC) and nutrient (NPK) content based on stake damage class in pine and mahogany stands of the Alas Bromo Educational Forest

Damage class to stakes	SOC (%)	SOC (%)	Total-P (mg/100g)	Total-K (mg/100g)
		Pine stand 1994		
Control	2.07[ab]±0.08	0.18[a] ±0.02	4.15[bc]±0.15	19.65[ab]±0.08
0	1.86[a] ±0.03	0.18[a] ±0.05	4.03[ab]±0.17	18.28[a] ±0.03
1	2.09[ab]±0.05	0.22[ab]±0.06	3.80[a] ±0.36	21.42[ab]±0.05
2	2.09[a] ±0.20	0.30[c] ±0.05	4.40[c] ±0.11	26.47[ab]± 0.20
3	2.26[a] ±0.37	0.26[bc]±0.07	4.33[bc]±0.18	24.12[bc]±0.37
4	2.49[b] ±0.03	0.40[d] ±0.03	4.84[d]±0.25	32.32[c]± 0.03
		Pine stand 1973		
Control	1.11[a] ±0.06	0.24[a] ±0.03	4.19[a] ±0.10	13.49[a] ±0.05
0	1.05[a] ±0.05	0.24[a] ±0.02	3.81[a] ±0.27	12.82[a] ±0.05
1	1.16[ab]±0.06	0.28[a] ±0.04	7.04[bc]±0.43	14.19[ab]±0.06
2	1.24[b] ±0.08	0.28[a] ± 0.30	6.16[b] ±1.58	18.20[b] ±0.08
3	1.41[a] ±0.12	0.35[b] ±0.03	6.51[bc]±0.77	26.51[c] ±0.12
4	1.48[c] ±0.07	0.42[c] ± 0.02	7.63[c] ±0.26	28.88[c] ±0.07
		Pine stand 2001		
Control	1.32[a] ±0.09	0.20[a] ±0.01	6.3[ab]±0.44	18.33[a] ±0.09
0	1.31[a] ±0.08	0.20[a] ±0.05	5.87[a] ±0.28	23.76[a] ± 0.08
1	1.33[a] ±0.13	0.23[ab]±0.03	6.47[abc]±0.69	26.08[a] ±0.13
2	1.36[a] ±0.05	0.28[b] ±0.01	6.58[abc]±0.22	29.39[a] ±0.05
3	1.44[a] ±0.16	0.38[c] ±0.03	7.02[bc]±0.14	37.97[a] ±0.15
4	1.81[b] ±0.03	0.41[c] ±0.05	7.22[c] ±0.78	45.58[b]±0.03
		Pine stand 2016		
Control	1.17[a] ±0.07	0.27[ab]±0.03	5.05[a] ±0.10	18.32[a] ±0.07
0	1.27[a] ±0.06	0.28[ab]±0.04	4.82[a] ±0.17	16.95[a] ±0.06
1	1.33[a] ±0.06	0.26[a] ±0.04	7.09[ab]±3.26	14.50[a] ±0.06
2	1.34[a] ±0.16	0.31[bc]±0.03	5.53[ab]±0.27	15.03[a] ± 0.16
3	1.32[a] ±0.11	0.34[c] ±0.03	7.55[b] ±1.05	15.66[a] ±0.10
4	1.70[b] ±0.45	0.39[d] ±0.02	12.91[c] ±0.95	20.49[b] ± 0.45
		Mahogany stand 1973		
Control	2.2[ab]±0.17	0.25[a] ±0.02	4.08[a] ±0.17	17.86[a] ±0.17
0	2.12[a] ±0.07	0.25[a] ±0.03	7.10[a] ±0.13	18.04[a] ±0.07
1	2.15[ab]±0.06	0.29[ab]±0.03	5.91[bc]±0.15	26.29[a] ±0.06
2	2.25[ab]±0.13	0.35[b] ±0.06	8.56[b] ±1.74	27.58[a] ±0.13
3	2.28[bc]±0.09	0.32[ab]±0.07	8.77[bc]±0.33	23.03[a] ±0.09
4	2.54[c] ±0.33	0.43[c] ±0.02	12.15[c]±0.21	34.25[b] ±0.32
		Mahogany stand 1949		
Control	2.29[a] ±0.03	0.27[a] ±0.03	4.08[a] ±0.17	43.11[a] ±1.21
0	2.24[a] ±0.27	0.28[a] ±0.02	3.52[a] ±0.18	42.63[a] ±1.50
1	2.32[a] ±0.04	0.28[a] ±0.04	3.81[a] ±0.13	40.40[a] ±7.33
2	3.4[b] ±0.11	0.35[b] ±0.01	4.53[b] ±0.09	60.87[b] ± 3.13
3	-	-	-	-
4	-	-	-	-

of soil fertility (Holt and Lepage 2000; Deke *et al*. 2016; Khan *et al*. 2018; Myer and Forschler 2019). Therefore, termites are considered soil engineers and soil bioturbators (Black and Okwakol 1997).

The highest values of SOC and NPK content were produced in the damage class of marker four, which indicates high termite activity. This positive correlation suggests that increased termite activity leads to higher SOC and NPK nutrient levels in the soil. Termite activity significantly influences soil chemistry, increasing organic carbon and nutrients like nitrogen, phosphorus, and potassium in infested soils (Rajeev and Sanjeev 2012; Lejoly *et al*. 2019), attributed to the role of termites in accelerating organic matter decomposition (Jones 1990; Issoufou *et al*. 2019).

The absence of damage classes 3 and 4 in the 1949 mahogany stand is due to the natural resistance of mahogany wood to termite attacks (Badawi *et al*. 1984).

Figure 3. Termite-built soil from pipes in the Alas Bromo Educational Forest

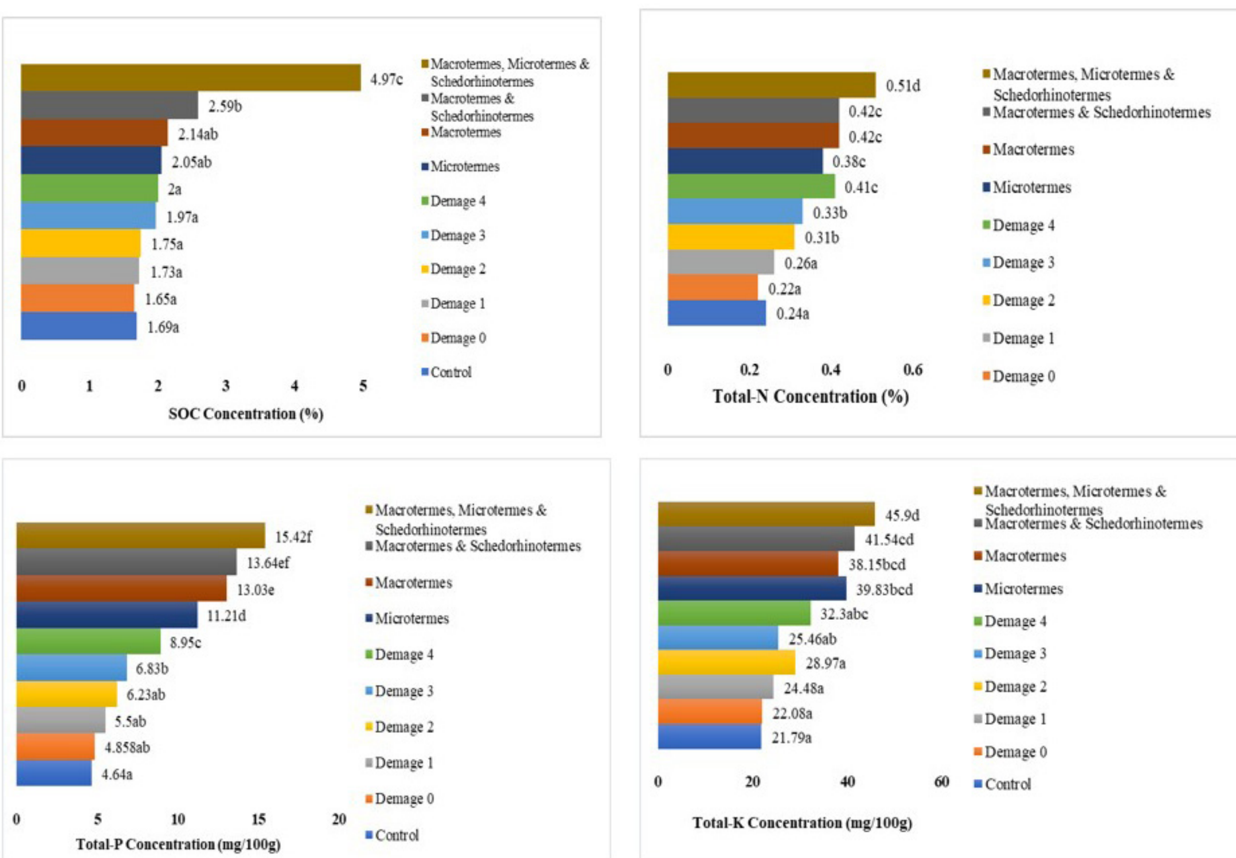

Figure 4. Comparison of soil organic carbon (SOC) and total NPK content in soil based on termite genus and stake damage class across all stands in the Alas Bromo Educational Forest

However, the SOC and total N content in damage class 2 of the 1949 mahogany stand were higher compared to the pine stands, which can be attributed to the faster decomposition rate of mahogany litter compared to pine needles. Pine litter has an isohumic value or compounds that are relatively more stable and not easily decomposed (0.65), which is higher than other forests, indicating a longer retention time in the litter decomposition process (McClain *et al*. 1996).

Research conducted in Alas Bromo found various termite genera such as *Microtermes* sp., *Macrotermes* sp., *Schedorhinotermes* sp., and *Odontothermes* sp. Termites, especially in tropical areas, contribute to the soil humification process by modifying the concentration of organic matter so that there is an increase in the overall organic matter cycle (Brauman 2000). Another study in the highlands of southwestern Ethiopia also confirmed that termite activity can improve soil chemistry, primarily organic carbon and soil nutrients (Jembere *et al*. 2017). Termites of the genus *Macrotermes* sp. and *Microtermes* sp. decompose organic matter through symbiotic relationships with basidiomycete fungi of the genus *Termitomyces* (Taprab *et al*. 2005). Meanwhile, *Schedorhinotermes* produce enzymes in their intestines to carry out the digestion and decomposition of organic matter (Pest-ex n.d). This can be a factor why the highest nutrient value is produced in soils with a combination of the genus *Schedorhinotermes* sp.

Termites support nitrogen fixation indirectly through symbiosis with nitrogen-fixing bacteria such as *Azotobacter* and *Bacillus* (Nithyatharani and Kavitha 2018). Termite-influenced soil is known as a soil nutrient hotspot because of termite activity that increases the decomposition of organic matter (Abe *et al*. 2011). Through the help of bacteria such as *Azotobacter* and *Bacillus*, which play a role in binding nitrogen, termites decompose organic matter (Sathiya *et al*. 2018). This activity produces nutrients for termite mound soil, resulting in the accumulation of organic carbon, as well as nitrogen and potassium nutrients in the mound soil (Jouqueta *et al*. 2011).

The value of NPK nutrients in termite-formed soil is higher compared to other soils. These results are consistent with the findings of Indrayani *et al*. (2021), who reported that termite activity can improve soil chemical properties, including organic carbon (up to 2.97%), total nitrogen (up to 0.23%), available phosphorus (up to 194.48 mg/kg), and potassium (up to 7.77 cmol/kg). Another study conducted by Mosaku *et al*. (2024) in Ogun State, Nigeria, West Africa, showed that soil in termite mounds produced a SOC value of 1.2%, a total phosphorus value of 10.01 mg/100 g, and a total nitrogen content of 1.71. The pH value of the soil ranged from 6.45 to 7.54, while that of the surface soil ranged from 6.03 to 7.09. This indicates that termite activity does not affect soil pH. The study by Febriani *et al*. (2025) also showed that termite activity did not significantly affect soil pH conditions.

Termites are recognized as key ecosystem engineers in tropical regions, where their activities significantly enhance soil quality through the accumulation and decomposition of organic matter (Apori *et al*. 2020), and termite activity increases the content of organic carbon, nitrogen, phosphorus, and potassium in the soil they inhabit (Rajeev & Sanjeev 2012). Termites in tropical ecosystems play a crucial role in nutrient cycling (Chen *et al*. 2021), making them a valuable source of nutrients for increasing soil fertility in agricultural activities, such as those of smallholder farmers in Uganda (Apori 2020) and Cambodia (Muon *et al*. 2022).

This study highlights the critical role of termites as soil engineers in tropical forest ecosystems, demonstrating their contribution to increasing soil organic carbon (SOC) and NPK nutrient content. Termite activity, particularly from the genera Macrotermes, Microtermes, and Schedorhinotermes, significantly enriches soil nutrients and highlights the importance of termite ecology in influencing soil fertility. From a practical perspective, this suggests that termite-processed soil could serve as a cost-effective and environmentally friendly soil amendment to enhance agricultural productivity, particularly on degraded lands with low soil nutrient content. Additionally, future research could directly test the effects of adding termite-formed soil to farming fields and degraded lands. Such studies may reveal whether this approach can increase crop yields, aid in land restoration, and reduce reliance on synthetic fertilisers, thereby offering a sustainable strategy for agricultural development and ecosystem rehabilitation.

One limitation of this study is the relatively short exposure period, which was only two weeks. This limited duration may not fully represent seasonal variations in termite foraging activity, which can be influenced by factors such as rainfall patterns, soil moisture, and temperature fluctuations throughout the year. The short observation period also limits the study's ability to capture the long-term dynamics of termite–soil interactions. Therefore, further research is needed.

Acknowledgements

This research can be carried out because there is funding support from Universitas Sebelas Maret Fundamental Research (PF) grant with letter number: 369/UN27.22/PT.01.03/2025. We would also like to thank the Management of Alas Bromo for allowing us to conduct research in the area.

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