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Termite activity in tropical and subtropical Brazilian soils

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ABSTRACT. Termites, key members of the soil macrofauna, play a significant role in bioturbating soil through their construction activities, essential for their mobility and survival. Despite extensive studies on the alterations caused by mound construction, the full impact on soils, particularly in the Americas, remains inadequately understood. This study hypothesized that termites selectively engage with specific soil materials, a theory tested by comparing the sand and clay fractions of soils and mounds at six sites across five Brazilian states. Sedimentological analyses were performed on the sand fraction, while the mineral fraction underwent X-ray diffraction, magnetic susceptibility, and selective iron oxide dissolution tests. The findings reveal that termites prefer smaller sand particles when constructing mounds in sandier soils. In most locations, termites concentrated up to 79.9% of Fe and 65.3% of Al from pedogenic iron and aluminum oxides, and up to 31.1% of Fe from poorly crystalline forms. Magnetic susceptibility measurements indicated minimal differences in magnetic minerals between mounds and soils. Termites do not alter the mineral composition of highly weathered soils, which primarily consist of kaolinite, gibbsite, and iron oxides. However, they selectively target clay-sized particles in sandy soils. Therefore, termites are not considered weathering agents in highly weathered soils dominated by stable minerals. These results underscore the significant role of termites as bioturbators in soil dynamics.

Keywords: macrofauna; mineralogy; X-ray diffraction; sand sedimentology.

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Introduction

Termites, invertebrate members of the soil macrofauna, construct subterranean and epigeal structures that facilitate their movement and survival in the soil. Over time, these structures degrade and merge into the surrounding soil (Jouquet et al., 2011). Due to their impact on soil structure, termites are recognized as "ecosystem engineers" (Bignell & Eggleton, 2000; Jouquet et al., 2011; Jouquet et al., 2016a). Although the effects of ants and worms on soil have been well-documented, the influence of termites remains less understood (Lobry de Bruyn & Conacher, 1990; Jouquet et al., 2016a).

Previous research indicates that termites selectively gather organic materials, clay-sized particles, and essential nutrients from the soil to construct their mounds, with preferences varying by soil type, environmental conditions, and the specific feeding behaviors of the termite species (Ferreira et al., 2011; Jouquet et al., 2015; Jouquet et al., 2016b). In various positions and types of vegetation within the Brazilian Atlantic Forest, termite activity has enhanced nutrient and organic carbon levels, cation exchange capacity, and the proportion of clay in the mounds (Sarcinelli et al., 2013; Lima et al., 2018). Similar increases in nutrient and organic carbon concentrations have been observed at the centers of termite mounds across five sites in southern Brazil (Kaschuk et al., 2006). In the Congo Ferralsols, termite activity raised the levels of 2:1 clay minerals and manganese and iron oxides within the mounds. Research into "murundus" earth mounds in Brazil's semi-arid regions found that long-term termite activity is the primary process in their formation, which also features higher clay, nutrient, and organic carbon content (Souza et al., 2020).

Moreover, termites are considered agents of weathering. Controlled experiments have shown that termites increase the expansiveness of interlayers in 2:1 clay minerals (Jouquet et al., 2002). When illite was introduced as a substrate to a principal termite species in West Africa, the resultant termite mounds showed the transformation of illite by the extraction of interlayer potassium, leading to the formation of smectite layers (Jouquet et al., 2007). However, in some cases, their actions do not appear to significantly alter the sand, silt, or clay content between soils and mounds (Kaschuk et al., 2006).

Despite their widespread presence in Brazil and South America, termites have been less studied there compared to Asia or Africa. This study aimed to compare soil and termite mound materials through sedimentological analysis of the sand fraction, X-ray diffractometry, and magnetic susceptibility, combined with selective chemical dissolution of iron oxide minerals. The initial hypothesis posited that termites selectively utilize soil materials to construct their mounds, an assertion tested by examining the differences and similarities in the sand and clay fractions between soils and mounds across various Brazilian regions.

Material and methods

Soil and mound samples were collected from six distinct locations across various Brazilian regions (Table 1). Control soil samples were taken from the 0.00-0.40 m depth layer in triplicate under natural vegetation near the termite mounds (15 to 30 meters away) where termites showed no visible activity. Termite mound samples were also collected in triplicate from both the top and middle sections of active epigeal mounds, whose heights ranged between 0.60 and 1.65 meters. All samples were air-dried, ground, and sieved through a 2 mm mesh to procure the air-dried fine earth (ADFE) fraction.

In the regions of EA, MG, and MT (Table 1), the specimens were identified as belonging to the genus Cornitermes, which has a litter and soil-feeding habit. Other identified genera included Cortaritermes (grass-feeding habit) in RS, Syntermes (litter and soil-feeding habit) in PI, and Labiotermes (soil-feeding habit) in PA. For a more comprehensive description of the sampling and sample preparation methods, refer to Fruett et al. (2023).

Table 1. Code and geographic location of soil and termite mound samples, as well as environmental conditions, original material, soil class, and clay content.

Sample code	Municipality/State	Geographic location	Parent material	Soil class[1]	Climate[2]	$\bar{X}$ t°[3] °C	$\bar{X}$ ppt[4] mm	Vegetation	Clay[5] g kg^{-1}
RS	Júlio de Castilhos/RS	29° 6'1.52" S 53°37'19.36" W	Basalt/ Sandstone	Rhodic Ferralsol	Cfa	18.0	1,575	Pampa (grasslands)	300
EA	Eldorado do Sul/RS	30° 6'10.84" S 51°40'33.80" W	Granite	Rhodic Acrisol	Cfa	19.5	1,309	Pampa (grasslands)	295
MG	Lavras/MG	21° 12'18.03" S 44°59'36.95" W	Gabbro	Rhodc Ferralsol	Cwa	19.0	1,530	Cerrado (woody-grasslands)	470
PI	Cristino Castro/PI	8° 51'13.30" S 44°17'36.07" W	Sandstone	Xanthic Ferralsol	Aw	26.7	849	Caatinga-Cerrado contact	210
PA	Santana do Araguaia/PA	9°41'36.52" S 50°57'31.11" W	Granite	Haplic Acrisol	Am	27.5	1,919	Amazônia (Ombrophilous forest)	170
MT	Canabrava do Norte/MT	11° 0'39.66" S 51°38'7.33" W	Recent sediments	Gleyic Arenosol	Am	27.0	1,578	Cerrado (woody-grasslands)	50

[1]WRB (IUSS Working Group WRB, 2015); [2]Cfa-temperate without dry season; Cwa-temperate with dry winters; Am-tropical monsoon; Aw-tropical savannah; [3]Annual average temperature; [4]Annual average rainfall; [5]Fruett et al. (2023).

Sand fraction (0.05–2.00 mm) was separated by wet sieving through a 0.053-mm mesh after dispersing ADFE in 1 mol L^{-1} NaOH and drying at 105°C for 24 hours (Teixeira et al., 2017). The process was followed by mechanical stirring for 30 seconds to obtain five subfractions: very coarse (2.00–1.00 mm), coarse (1.00–0.50 mm), medium coarse (0.50–0.25 mm), fine (0.25–0.106 mm), and very fine (<0.106 mm) sand. Each fraction was weighed, with results expressed as a percentage of the total sample weight. Sand sedimentology analysis used SYSGRAN 3.0® software to calculate distribution and cumulative frequencies. Sedimentological parameters were determined based on classification by Folk and Ward (1957), including average particle size, degree of selection (particle size distribution), skewness (asymmetry of particle size distribution), and kurtosis (sharpness of the distribution curve into mesokurtic, leptokurtic or platykurtic). These results were interpreted according to Suguio (1973).

Total clay was obtained by sedimentation based on Stokes' law. Clay samples underwent triple washing with a 92.8% alcohol and distilled water mix (1:1 ratio) and were dried at 50°C. A 2-g portion of the clay fraction was treated with a mixture of 2 g sodium dithionite, 45 mL sodium citrate (0.3 mol L^{-1}), and 5 mL sodium bicarbonate (1 mol L^{-1}) to selectively extract iron oxides and produce deferrified clay.

Low-frequency magnetic susceptibility (0.47 kHz - χLF) was measured for the ADFE fraction from both soil and mounds using a Bartington magnetometer equipped with an MS2B dual frequency sensor (Torrent et al., 2006). Structural Fe and Al in total pedogenic iron oxides (Fed) were extracted from 200 mg ADFE using a DCB mixture (1 g sodium dithionite, 45 mL sodium citrate (0.3 mol L^{-1}), 5 mL sodium bicarbonate (1 mol L^{-1}) at 80°C (Mehra & Jackson, 1960). Poorly crystalline Fe and Al (Feo and Alo) were extracted using 50 mL of ammonium oxalate (0.2 mol L^{-1}) at a pH of 3 in the dark (Schwertmann, 1964). The concentrations of Fe and Al in these extracts were determined by inductively coupled optical emission spectrometry (ICP-OES).

The mineralogical composition of ADFE, clay, and deferrified clay fractions in both soils and mounds was determined using a Bruker D2-Phaser XRD instrument equipped with an LYNXEYE™ detector and DIFFRAC.SUITE™ software. The spectrometer utilized Cu κα radiation (λ = 1.5418 Å), and voltage and current were held at 30 kV and 10 mA. Slides were made from disordered powdered material, using identical amounts of soil and mound from each site. Measurements were taken at intervals of 0.02° 2θ s^{-1} across a range of 4–50° 2θ. Mineral reflections were identified based on criteria given by Brown and Brindley (1980). Differences between soil and mound components were assessed using differential X-ray diffraction (DXRD) analysis (Inda Junior & Kämpf, 2005), which involved subtracting mound XRD measurements from corresponding soil data. The presence of additional mineral content in soil or mounds resulted in positive or negative reflections in the DXRD spectra.

Analysis of variance was applied to the data on average Fe and Al contents extracted by ammonium oxalate and by sodium dithionite-citrate-bicarbonate in soil and mound samples, with mean differences evaluated using the Tukey test ($p < 0.05$).

Results and discussion

Sand sedimentology

The sedimentological parameters for the sand fraction in both soil and mound samples from sites RS, EA, and MG (Table 2) — which had clay contents exceeding 300 g kg^{-1} (Table 1) — were identical. In contrast, sites PI, PA, and MT, characterized by sandier soils (clay contents not exceeding 300 g kg^{-1}; Table 1), showed differences in average diameter, degree of selection, asymmetry, and kurtosis between soil and mound samples (Table 2). Notably, the degree of selection in PI was poor for soil but moderate for the mound, while in PA it was the opposite. Furthermore, the average particle diameter in MT was medium for the soil but fine for the mound. This finding is particularly significant given the limited research on sandy soils of this type (Sarcinelli et al., 2013).

Table 2. Particle size distribution of sand in soils (S) and mounds (M).

Sample	Average diameter		Degree of selection		Asymmetry		Kurtosis	
	ϕ	Class	σ (ϕ)	Class	Value	Class	Value	Class
RS-S	1.69	Medium sand	0.68	Moderate	−0.30	Negative	1.01	Mesokurtic
RS-M	1.71	Medium sand	0.67	Moderate	−0.22	Negative	1.01	Mesokurtic
EA-S	1.04	Medium sand	1.20	Poor	0.00	Roughly symmetric	0.65	Highly platykurtic
EA-M	1.00	Medium sand	1.22	Poor	0.05	Roughly symmetric	0.62	Highly platykurtic
MG-S	1.47	Medium sand	1.13	Poor	−0.13	Negative	0.97	Mesokurtic
MG-M	1.84	Medium sand	1.05	Poor	−0.12	Negative	0.99	Mesokurtic
PI-S	1.41	Medium sand	1.01	Poor	−0.12	Negative	1.01	Mesokurtic
PI-M	1.54	Medium sand	0.89	Moderate	−0.14	Negative	1.04	Mesokurtic
PA-S	1.31	Medium sand	0.98	Moderate	−0.19	Negative	0.94	Mesokurtic
PA-M	1.09	Medium sand	1.17	Poor	−0.03	Roughly symmetric	0.68	Platykurtic
MT-S	1.91	Medium sand	0.55	Moderate	−0.11	Negative	1.26	Leptokurtic
MT-M	2.05	Fine sand	0.76	Moderate	0.01	Roughly symmetric	1.21	Leptokurtic

Figure 1 illustrates the frequency distribution of particle diameters along with the results for asymmetry and kurtosis. It is evident that termite activity did not modify the asymmetry in constructing mounds at RS, MG, or PI, where asymmetry remained negative; nor was it altered at EA, where the distribution was roughly symmetric. However, at sites PA and MT, asymmetry shifted from negative in the soils to roughly symmetric in the mounds, indicating a higher frequency of coarse particles in the soils compared to the mounds. Kurtosis showed variation only at PA, where the soil exhibited a mesokurtic distribution and the mound was platykurtic, reflecting a higher frequency of smaller particles in the mound. Despite both soil and mound at MT being leptokurtic, the mound displayed a greater prevalence of small particles.

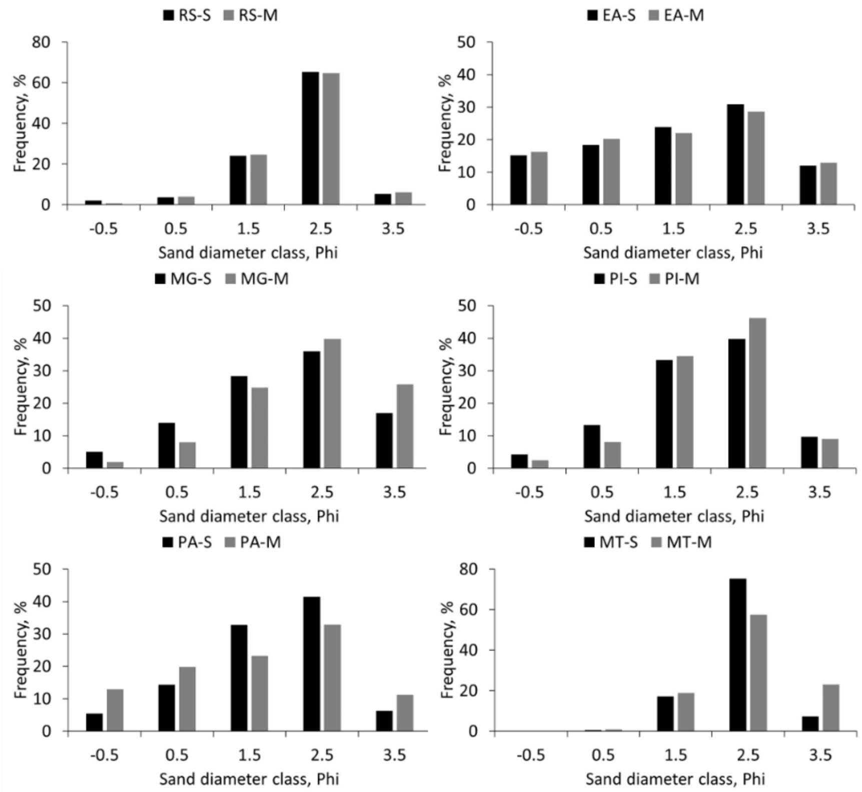

Figure 1. Frequency distribution of sand particles in soils (S) and mounds (M) across the six sites.

Figure 2 presents the cumulative frequency for the sand subfractions of soils and mounds. The cumulative frequency for sites RS and EA exhibit very close similarity, suggesting that termites at these locations did not show selectivity towards different sand fractions. Conversely, at sites MG and PI, the cumulative frequency for the soils generally lie above those for the mounds, indicating a higher frequency of larger particles in the soils. This trend was particularly pronounced at MT, where there was a noticeable increase in the frequency of smaller particles in the mounds, although this was less evident at PA.

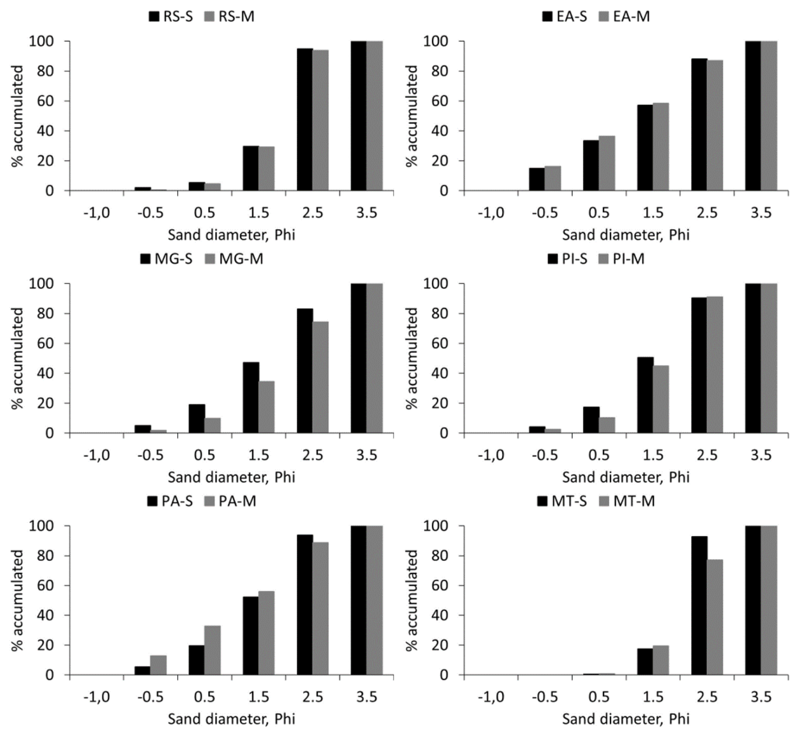

Figure 2. Cumulative frequency of sand particles in soils (S) and mounds (M) across the six sites.

According to Suguio (1973), while the differences in sedimentological parameters between soil and mound at the sandier sites are not extensive, they do indicate a preference by termites for using smaller particles in mound construction. This preference likely stems from the limited availability of silt- and clay-sized particles in these environments.

Selective dissolution of iron oxides

At most sites, the concentrations of pedogenic iron oxides (Fed) and poorly crystalline iron oxides (Feo) were higher in the mounds than in the surrounding soils (Table 3). However, an exception was noted at site PA, where Feo concentrations were higher in the soil. This site experiences an annual average rainfall of nearly 2,000 millimeters (Table 1), primarily concentrated in the first half of the year. Mujinya et al. (2013) observed similar increased Feo contents in mounds in the Congolese region of Lubumbashi, attributing this to prolonged water residence times in mounds compared to surrounding soils, which facilitates more intense oxidation-reduction cycles.

The contents of structural aluminum present in iron oxides (Ald) mirrored those of Fed, being higher in the mounds at all sites except PA. Furthermore, the concentrations of aluminum in poorly crystalline forms (Alo) were consistent between soils and mounds across all sites. Table 4 displays the mound-to-soil ratios for Fed, Ald, Feo, and Alo contents, with ratios above one indicating higher concentrations in mounds compared to soils. These results align with previous studies, which have consistently reported increased clay contents in mounds — clay being the fraction where iron oxides predominantly accumulate — compared to the originating soils (Jouquet et al., 2002; Abe & Wakatsuki, 2010; Ferreira et al., 2011; Lima et al., 2018).

Table 3. Structural iron and aluminum contents in pedogenic (Fed and Ald) and poorly crystalline iron oxides (Feo and Alo), and low-frequency magnetic susceptibility (χ_{LF}) in the fine fraction of soils (S) and mounds (M).

Sample	DCB		Ammonium oxalate		χ_{LF} ($m^3\ kg^{-1}$) ×10^{-7}
	Fed	Ald	Feo	Alo	
	g kg^{-1}				
RS-S	27.91*	4.95*	3.41	4.17	39.5*
RS-M	30.76	5.21	3.62	3.95	34.1
EA-S	18.80*	3.66*	2.85	3.01	7.0
EA-M	26.72	4.56	3.31	3.13	8.2
MG-S	140.28	17.76	7.35	7.07	479.5*
MG-M	163.60	22.61	7.38	6.56	436.0
PI-S	6.58*	1.14*	0.49*	0.85	0.3
PI-M	32.48	3.29	0.68	0.94	0.5
PA-S	11.98	3.29*	3.92*	1.92	1.2
PA-M	12.46	2.30	1.65	1.50	1.1
MT-S	11.85*	1.55*	3.41*	0.88	0.3*
MT-M	15.95	3.86	4.95	1.02	0.9

*Significant difference between the soil and mound averages by the Tukey's test ($p < 0.05$).

Table 4. Mound-to-soil content ratio (M/S) for elements extracted by selective dissolution across the six sites evaluated.

Site	DCB		Ammonium oxalate	
	Fed	Ald	Feo	Alo
	M/S		M/S	
RS	1.10	1.05	1.06	0.95
EA	1.42	1.25	1.16	1.04
MG	1.17	1.27	1.00	0.93
PI	4.94	2.89	1.39	0.92
PA	1.04	0.70	0.60	0.98
MT	1.35	2.49	1.45	1.11

Magnetic susceptibility

As indicated in Table 3, magnetic susceptibility (χ) was notably high at RS and MG, where the soils are derived from basalt/sandstone and gabbro, respectively. At these sites, χ was higher in the soils compared to the mounds. This can be attributed to termites' tendency to concentrate clays in their mounds (Lima et al., 2018), potentially leading to a relative depletion of magnetite, which is often found in the coarser silt and sand fractions of basic rocks. Consequently, this might result in lower χ values in the mounds.

Conversely, at other sites where soils developed from acidic or sedimentary rocks, χ values were lower (Table 3). The magnetic susceptibility was similar in soils and mounds at EA, PA, and PI. However, at MT, χ

was higher in the mounds, possibly due to the absence of magnetite in the coarse fractions and an increase in clay content — along with pedogenic iron oxides such as ferromagnetic maghemite — enriching the mounds.

X-ray diffraction spectra

XRD spectra revealed minimal mineralogical composition differences between soils and mounds at all sites. This is likely due to the high stability of clay minerals present, such as kaolinite and gibbsite (Kaschuk et al., 2006). Despite using an identical weight of soil and mound material from each site for analysis, XRD intensity variations were observed between soils and mounds, with differences in magnitude across sites. This finding aligns with previous research by Abe and Wakatsuki (2014) on soil and mound samples from central Nigeria.

According to the XRD reflection intensities for the ADFE fraction (Figure 3), quartz was the predominant mineral in all soils, except for those at MG, which developed from basalt, underscoring its resistance to weathering. Although kaolinite was present in all soils, the intensity of its XRD lines varied between sites. At MG, gibbsite and hematite were the dominant minerals, while feldspars were only detected at RS. The XRD lines for quartz and feldspar were stronger in the soils than in the mounds, reflected in the quartz lines at most sites and feldspar lines at RS. Negative reflections in the differential spectra indicated that kaolinite lines were more pronounced in the mound spectra at PI, MT, and PA, suggesting that termites preferentially concentrate kaolinite, thereby indicating a higher selectivity for clay-sized particles over coarser materials such as quartz or feldspars. Conversely, the absence of significant kaolinite lines in the differential spectra for RS, EA, and MG suggests that the mineral composition of soils and mounds at these sites was similar.

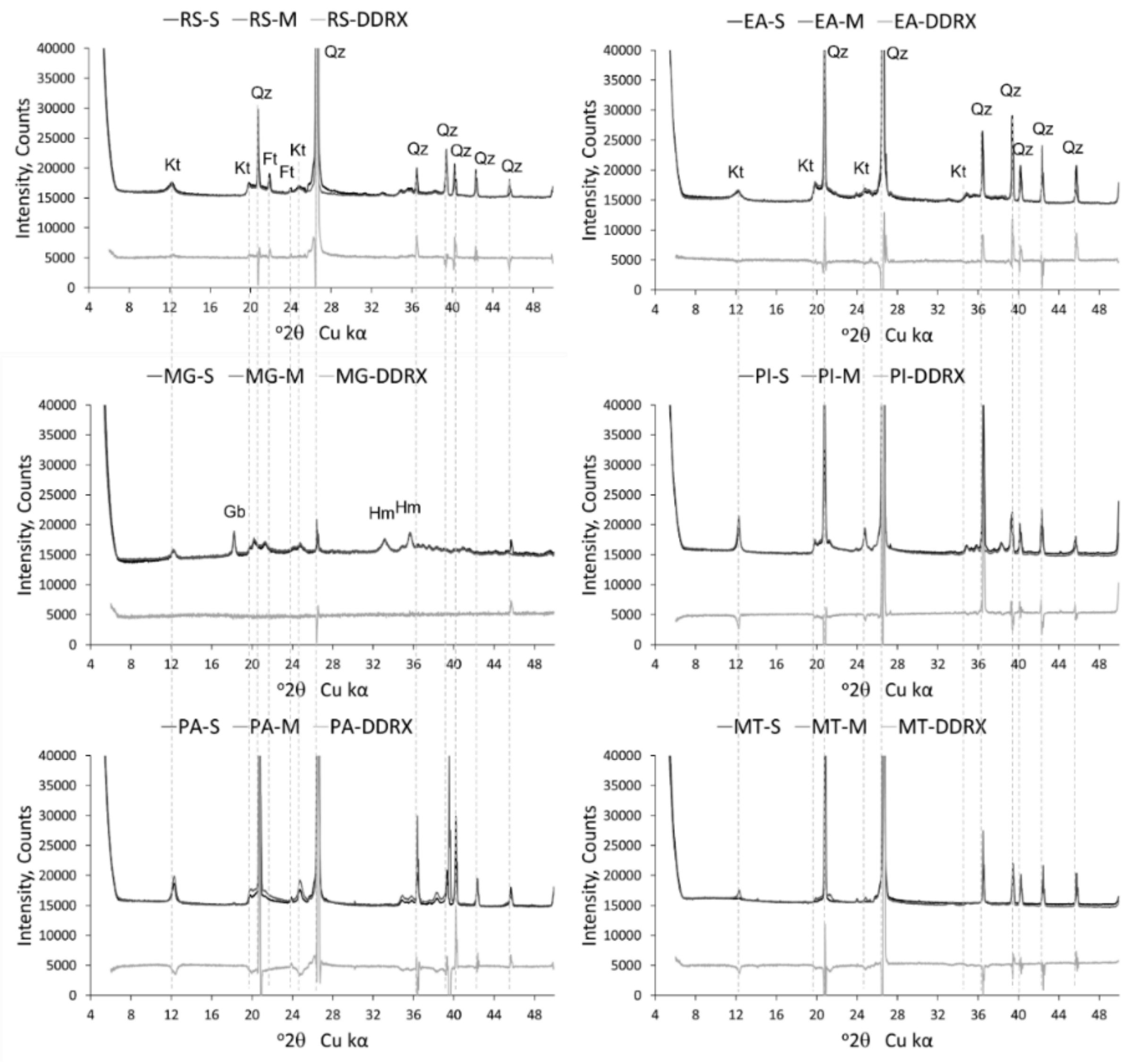

Figure 3. XRD patterns for ADFE fraction of soils (S) and mounds (M) and respective differential XRD spectra (M−S) for samples collected at six sites.

The XRD findings for the ADFE fraction show that soil and mound materials at sites with clay soils (RS, EA, and MG) were similar, while those at sites with sandier soils (PI, MT, PA) demonstrated an increased termite selectivity for clay-sized particles. This pattern is consistent with the findings of Abe and Wakatsuki (2014) for soils derived from sandy sediments, confirming a broader pattern of termite behavior in selecting finer particles for mound construction.

The ADFE fraction findings closely corresponded with those of total clay, as illustrated in Figure 4, top panel. The intensities of XRD lines for kaolinite, gibbsite, and hematite in samples from RS, EA, and MG were similar, indicated by the nearly horizontal differential curves in the XRD spectra (notably at point EA in Figure 4, top). Moreover, the XRD lines for total clay reinforced the selective behavior of termites towards kaolinite when constructing their mounds. This is demonstrated by the strong negative reflections for kaolinite in the differential XRD spectra from PI, MT, and PA (highlighted at point PA in Figure 4, top).

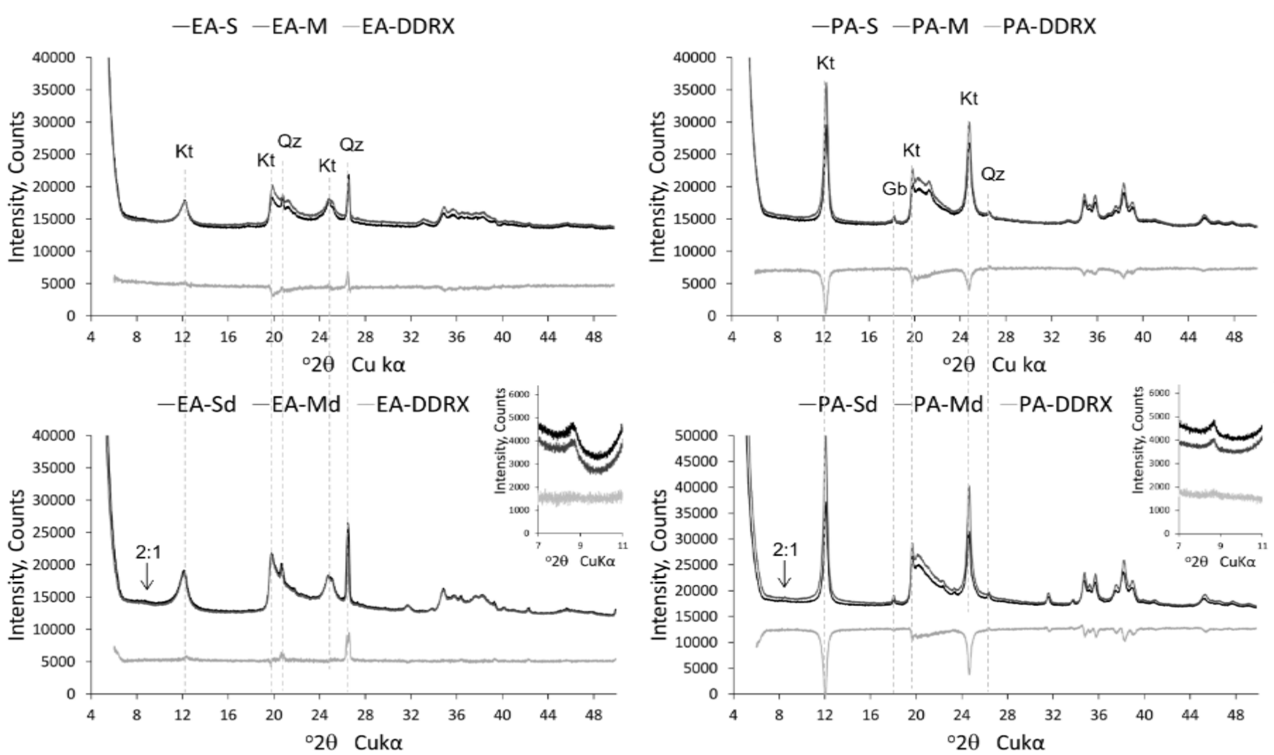

Figure 4. XRD patterns for disordered total clay (top) and deferrified clay (bottom) from soil (S) and mound (M) samples and respective differential XRD spectra (M–S) for sites EA (left) and PA (right). The insets displaying the XRD patterns for the oriented clay fraction specifically highlight the region of 2:1 clay minerals.

Selective extraction of iron oxides from the materials at four sites facilitated the observation of weak reflections for 2:1 clay minerals (specifically smectites or vermiculites) at EA, MG, and PA, as depicted in the lower portion in Figure 4. However, these reflections were absent in the differential spectra for both disordered and ordered deferrified clay fractions (noted in the inset in Figure 4, bottom). This absence indicates that termites did not significantly alter these minerals in their mound construction or soil modification processes.

In contrast to these findings, research by Jouquet et al. (2007) documented that termite colonies in Africa can extract potassium from the interlayers of illite, a 2:1 clay mineral. The lack of observable changes in the 2:1 clay minerals in the current study could be attributed to their enhanced stability, possibly due to the occupation of their interlayers by aluminum polymers, as suggested by Azevedo et al. (2012), or their low contents in the soils.

Conclusion

Termites demonstrate a preference for smaller sand particles in sandier soils. At the majority of the sites studied, these insects accumulated iron (Fe) and aluminum (Al) from pedogenic iron oxides, as well as iron from poorly crystalline forms. Magnetic susceptibility measurements indicated that magnetic minerals showed minimal variation between soils and mounds. Furthermore, termites did not modify the mineral composition of highly weathered soils, which are predominantly composed of kaolinite, gibbsite, and iron oxides. However, they selectively targeted clay-sized particles in sandy soils.

Acknowledgements

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