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Termite diversity and infestation levels on *Eucalyptus pellita* plantations in Riau, Indonesia

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Abstract. *Prastyaningsih SR, Hardiwinoto S, Musyafa, Prehaten D, Effendy I, Ridwan N, Aini FK, Benatar GV. 2025. Termite diversity and infestation levels on* Eucalyptus pellita *plantations in Riau, Indonesia. Biodiversitas 26: 5495-5504. Eucalyptus pellita* is used in industrial plantations due to its high productivity. However, monoculture plantations are vulnerable to termite infestations, which can reduce wood volume. This study aimed to assess termite infestation in *E. pellita* plantations in Riau, Indonesia. A total of 5,791 trees were surveyed across 24 plots representing different stand ages to determine the incidence and intensity of termite damage. Specimens from infested trees were identified morphologically and molecularly using the mitochondrial cytochrome oxidase subunit II COII gene marker and phylogenetic analysis was applied to confirm species-level identification. Three termite species were identified: *Coptotermes sepangensis, Nasutitermes matangensis,* and *Microcerotermes havilandi*. Infestation was recorded in 3-4-year-old stands, with 5th rotation plots exhibiting greater severity than 4th rotation plots; among all species, *Microcerotermes* caused the greatest damage, followed by *Nasutitermes* and *Coptotermes*. Across all stands, 301 trees (5.2%) were found to be infested. Damage severity was assessed by observing trunk conditions, especially when termite mounds covered half or the entire diameter, and volume loss was estimated using Huber's formula. The highest infestation intensity (21.5%) occurred in the 4th rotation, although most cases were classified as mild (scale 1). In contrast, the 5th rotation showed higher infestation severity, with 12.3% of trees severely damaged (scale 4), resulting in the greatest wood volume loss. In 5th rotation, three-year-old tree showed the highest loss of volume, estimated at 9.10%, or 7.54 m³/ha. This is the first molecular confirmation (COII) report of termite infestation on *E. pellita* in Riau. The results provide baseline information on species composition, infestation patterns and associated wood loss in *E. pellita* plantations.

Keywords: COII, forest plantation, incidence, termite infestation

INTRODUCTION

The global pulp industry continues to grow (Beckline et al. 2016). In Indonesia, *Eucalyptus pellita* is one of the main raw materials for pulp and paper, widely cultivated in Sumatra, Kalimantan, and particularly important in Riau as one of the national pulp production centers (Inail et al. 2019; Hardiyanto et al. 2021). This species has replaced acacia plantations in the past decade due to its high productivity, making it central to the country's industrial plantation sector (Hardiyanto et al. 2021).

Termites play a crucial role in soil ecosystems by influencing soil structure and accelerating nutrient cycling (Chen et al. 2023). However, several termite species are also identified as agricultural pests (Govorushko 2019). In plantations, termites can attack trees by feeding on roots and stems, causing severe damage that can lead to tree mortality at various growth stages, whether young or mature (Fajar et al. 2021). Termites pose a considerable threat, particularly in monoculture plantations like oil palm and in industrial forest plantations (Akpesse et al. 2019). Monoculture practices make *Eucalyptus* vulnerable to termite attacks, causing significant damage and tree replacement depending on severity (Prastyaningsih et al. 2020). This deterioration changes the technological properties of the wood, including its chemical, physical, and mechanical characteristics (Kalleshwaraswamy et al. 2022).

In general, the main pests of wood-producing plants are termites. Economic losses caused by termite infestation are substantial; for example, invasive termites such as *Coptotermes* and *Cryptotermes* are estimated to cause over USD 40 billion annually in structural damage and control efforts worldwide (Chouvenc 2025). *Coptotermes* has long been reported as an important pest of *Eucalyptus* in the tropics (Ahmad et al. 2021; Alamu and Ewete 2023). The occurrence of different species of termites has been reported in *Eucalyptus* plantations in Nigeria where the foraging populations of *Ancistrotermes* and *Microtermes* species were very prominent and they attack plants through the roots and advance into the stem (Alamu et al. 2022)

The infestation of *Macrotermes gilvus* also causes infestation in oil palm plantations (Pashkevich et al. 2020).

Based on the study by Prastyaningsih et al. (2020), termites found in *Eucalyptus* stands in Riau, Indonesia, belong to two families, Termitidae and Rhinotermitidae. These termites are further classified into five subfamilies: Termitinae, Macrotermitinae, Nasutitermitinae, Rhinotermitinae, and Coptotermitinae. Scientific publications regarding the level of termite attack on *Eucalyptus* are still difficult to find (Prastyaningsih et al. 2020; Alamu et al. 2022). Accurate and specific studies regarding termite species that are pests of *E. pellita* are also very rarely carried out, especially in Indonesia, even though Riau represent one of the largest centers of industrial *Eucalyptus* plantations (Inail et al. 2019; Hardiyanto et al. 2021).

This study investigates the infestation of three species of wood-feeding termites on *E. pellita*. Not only were attack levels recorded, but the species were also identified based on morphological observations and molecular analysis. In addition, molecular confirmation through mitochondrial cytochrome oxidase subunit II COII markers strengthens species-level identification, reducing the risk of misclassification often encountered in purely morphological approaches. By combining morphological and molecular data, this study addresses a critical gap and provides new insights into the ecological behavior of termite pests in monoculture plantations.

Moreover, understanding termite-host interactions is crucial for developing integrated pest management strategies that are economically feasible and environmentally sustainable. This knowledge is expected to support integrated pest management strategies that are both economically feasible and environmentally sustainable for industrial forest plantations in Indonesia. This research also provides valuable baseline data for forest managers and policymakers, highlighting the potential ecological and economic impact of termite infestation on industrial timber plantations. By quantifying both the degree of infestation and the affected wood volume, this study aims to support decision-making in plantation management, minimize economic losses, and ensure sustainable supply for the pulp and paper industry.

The objectives of this study were to: (i) quantify the incidence and severity of termite infestation across stand ages and rotations in *E. pellita* plantations; (ii) identify termite species using both morphological characteristics and molecular analysis of COII markers; (iii) estimate the loss of usable wood volume caused by termite attack; and (iv) translate these findings into management implications for sustainable industrial plantation forestry in Riau.

MATERIALS AND METHODS

Study site and sample collection

The study was conducted from September 2021 to March 2022 in an industrial *E. pellita* plantation managed by PT Arara Abadi in Pelalawan District, Riau Province, Indonesia. Two plantation sites were selected: (i) Malako (0.063547°N, 102.191664°E; 20.4-55.6 m asl), representing a 4th rotation stand; (ii) Sorek (0.219375°N, 102.033186°E; 20.4-55.6 m asl), representing a 5th rotation stand.

Sites were selected to represent different rotation stages with similar soil and climatic conditions, accessibility for sampling, and documented termite infestations within the plantation area (R and D Departement). Sampling locations are shown in Figure 1. Transect locations were randomly selected within each age class to represent variation across the plantation area while maintaining comparable site conditions. At each site, transects measuring 100 m x 20 m (0.2 ha each) were established perpendicular to the slope and following the contour (Hardiwinoto et al. 2010) (Figure 1). For each age class (1, 2, 3, and 4 years old), three transects were established, resulting in 12 transects per site. With two rotations were used in this study, the total number of transects was 24, covering a total sampled area of 4.8 ha (24 transects x 0.2 ha each). Stand ages were obtained from company records, and all plots followed standard silvicultural management.

Specimens were preserved in 20 mL vials containing 70% ethanol and labeled with plot code, stand age, and tree number to maintain traceability between specimens and specific trees/plots. For each plot, 3-5 specimens per tree were collected, totaling 10-20 specimens per plot depending on termite activity.

Following the termite infestation survey, infestation data from all recorded trees including both infested and non-infested individuals, were used to estimate the impact of termite damage on merchantable wood volume without harvesting. For molecular analysis, 1-3 individuals per species per plot were sequenced to confirm species identity, ensuring that molecular data could be linked to specific trees and plots.

Morphological identification

Morphological identification of soldier castes was conducted under an Olympus SZ61 Microscope (Olympus Corporation, Tokyo, Japan) and photographed with an Optilab Advance system (PT. Miconos, Yogyakarta, Indonesia). Identification followed Tho (1992), based on head capsule dimensions, mandible shape, and pronotum morphology. Measurements were taken using a micrometer was calculated according to the method described by Mizumoto and Bourguignon (2021).

Molecular identification

DNA was isolated from the abdomen using the Qiagen DNeasy kit (www.qiagen.com) following the instructions provided. The DNA obtained was then amplified using the mitochondrial COII gene marker (Tseng et al. 2022). Sample DNA was amplified using One Taq 2X Master Mix with Standard Buffer (New England BioLabs Inc, Ipswich) following Polymerase Chain Reaction PCR instructions provided. The primer sequences used were forward: CI-J-2773 5'-ATA CCT CGA CG (AT) TAT TCA GA-3' and reverse: Reverse (B-tLys) 5'-GTT TAA GAG ACC AGT ACT TG-3'.

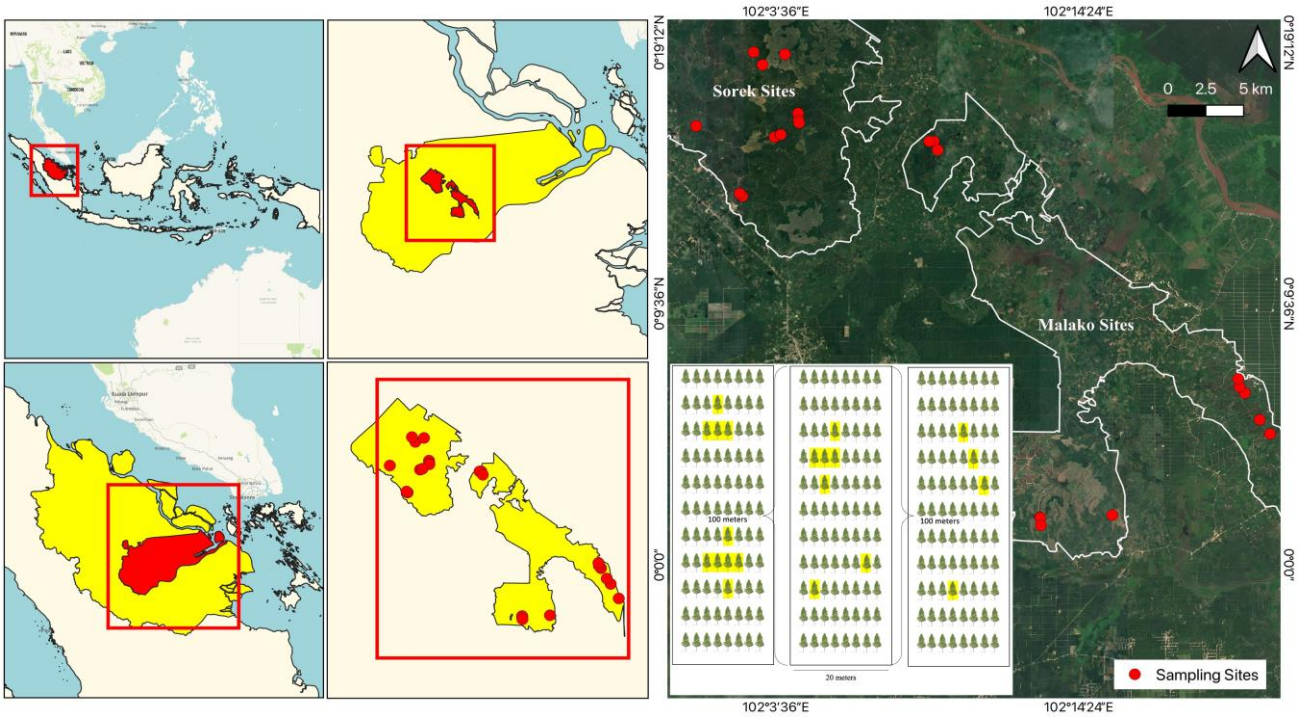

Figure 1. Map of survey and sampling locations. : Plot size 100x20 m, : *Eucalyptus pellita* stands, : *E. pellita* attacked by termites

The PCR thermal profile consisted of denaturation at 94°C for 3 min, followed by 35 cycles of 94°C for 30 s, 50°C for 30 s, and 72°C for 1 min, with a final extension at 72°C for 5 min. Confirmed PCR results using 1% (w/v) agarose gel on Wide Mini-Sub Cell GT Horizontal Electrophoresis System (BioLab, California) were sequenced using the Sanger method (LPPT UGM, Yogyakarta, Indonesia). The amplicon length was approximately 700 bp, and sequencing reads were verified for quality and coverage using standard chromatogram inspection and trimming protocols.

Sequence alignment and phylogenetic analysis

The DNA data from the sequencing results were then processed using the BioEdit v7.2.5 software. The phylogenetic tree was constructed using comparison sequences obtained from NCBI which were aligned using the ClustalW method on Mega X software 12, The Maximum Likelihood (ML) method with the Kimura 2-parameter model and 1000 bootstrap replications was used to construct the phylogenetic tree, *Mastotermes darwiniensis* was used as the outgroup. Each sample sequence has been deposited in GenBank under accession numbers PX436856 (*Coptotermes sepangensis*), PX436857 (*Microcerotermes havilandi*), and PX436858 (*Nasutitermes matangensis*) (Table 1).

Data analysis

Termite infestation assessment and wood loss

All trees within each plot were visually inspected for signs of termite attack. Trees were classified as attacked if one or more of following signs were observed: mud tubes, entry holes, galleries, frass or degraded bark/wood. Trees without these signs were classified as not attacked. Infestation severity was rated using a modified four-point scale adapted from Fajar et al. (2021): 1: Mild attack (superficial mud tubes, minor surface feeding, <10% of trunk affected); 2: Moderate attack (localized wood penetration, bark loss <50% of the trunk); 3: Severe attack (structure weakening, bark/wood loss ≥50%); 4: Mortality (tree death due to termite damage).

Inspection was conducted once during the sampling period by two trained observers and 10% of trees were rechecked by an independent observer to ensure consistency. Discrepancies were discussed and resolved jointly to standardize scoring. Representative termite specimens were purposively collected from active galleries or nests using purposive sampling.

DBH and height measurements

Tree measurement followed as standardized protocol: 1) Diameter at Breast Height (DBH) was measured at 1.3 m above the ground using a diameter tape rounded to the nearest 1 mm; 2) Branch-free height was measured using a vertex hypsometer, rounded to the nearest 0.01 m.

Tree volume was calculated using a modified Huber's formula (Zanetti et al. 2005; Inail et al. 2019).

$$Vt = f \times \left(\frac{\pi}{4}\right) \times dbh \times H$$

Where, Vt: Total stem volume (m^3); f: Form factor, set to 0.48 for *E. pellita* (Inail et al. 2019); DBH: Diameter at Breast Height (m); H: Total tree height (m).

Table 1. Species data from GenBank exploration used for phylogenetic construction

Family	Species	Isolate	Accession number	Location
Hodotermitidae	*Hodotermes mossambicus*	Hm464	MT211861	Germany
Hodotermitidae	*Microhodotermes viator*	-	AF220599	Australia
Kalotermitidae	*Neotermes humilis*	5ME1-5-1	MG781181	China
Kalotermitidae	*Cryptotermes declivis*	HN7	HQ012042	China
Mastotermitidae	*Mastotermes darwiniensis*	-	AB014071	-
Rhinotermitidae	*Coptotermes acinaciformis*	ISO1014	KJ918347	Australia
Rhinotermitidae	*Coptotermes formosanus*	LA6	FJ870592	Mississippi
Rhinotermitidae	*Coptotermes lacteus*	ISO750	KJ918292	Australia
Rhinotermitidae	*Cryptotermes tropicalis*	-	AF189095	Australia
Rhinotermitidae	*Reticulitermes labralis*	FT	JX142151	Beijing, China
Rhinotermitidae	*Coptotermes sepangensis*	MLA11	KU925214	Malaysia
Rhinotermitidae	*Coptotermes sepangensis*	-	COII_*Coptotermes*	Indonesia
Termitidae	*Aciculitermes maymyoensis*	t2859	AB109502	Japan
Termitidae	*Amitermes meridionalis*	-	AB240434	Japan
Termitidae	*Ancistrotermes pakistanicus*	w50A	AB109524	Japan
Termitidae	*Bulbitermes laticephalus*	w25A	AB109495	Japan
Termitidae	*Cornitermes cumulans*	Ccm254	MT188749	Germany
Termitidae	*Globitermes sulphureus*	Glo450	MT211860	Germany
Termitidae	*Havilanditermes proatripennis*	k96	AB109496	Japan
Termitidae	*Longipeditermes longipes*	-	AB011411	Japan
Termitidae	*Microcerotermes havilandi*	TBRU3	KY224610	Singapore
Termitidae	*Microcerotermes havilandi*	-	COII_*Microcerotermes*	Indonesia
Termitidae	*Nasutitermes longipennis*	H9	EF079019	Italy
Termitidae	*Nasutitermes matangensis*	BRU6	KY224715	Singapore
Termitidae	*Nasutitermes matangensis*	-	COII_*Nasutitermes*	Indonesia
Termitidae	*Nasutitermes walkeri*	-	AB037332	Japan
Termitidae	*Odontotermes formosanus*	Yuyong1	LC619257	Taiwan
Termitidae	*Odontotermes hainanensis*	YCH	JQ518443	China
Termopsidae	*Stolotermes* sp. *atherton*	-	AF262596	Japan

This approach assumes DBH as a representative diameter for the stem, adjusted by the form factor to correct for taper and bole shape. By applying (f: 0.48), the estimated volume accounts for the average stem form and merchantable portion of *E. pellita*.

The damage volume (Va) was approximated as a cylinder corresponding to the affected portion:

$$Va = F \times (\frac{\pi}{4}) \times da \times La$$

Where, Va: volume lost due to termite damage (m^3); F: damage factor was assigned based on the level of termite infestation for each tree/severity (light: 0.25, moderate: 0.5, severe: 0.75, and very severe or dead: 1.0); da: average diameter of the damaged portion of the stem (m); La: length of the damage portion of the stem (m).

Tree samples were categorized based on stage: U1: 1-year old trees, U2: 2-year-old trees, U1: 3-year-old trees, U4: 4-year-old trees. The termite infested wood was determined by measuring the damage portion and converting it into volume per hectare. Usable volume was obtained by subtracting the infested volume from the total tree volume.

All volumes were standardized to cubic meters per hectare (m^3/ha) and the proportion of volume loss was expressed as a percentage of total stand volume. Scaling to per hectare basis:

$$Vha = Vu \times (\frac{n\ trees}{A\ plot})$$

Where, Vha: Usable stem volume per hectare (m^3); N trees: Number of trees in the plot (ind); A plot: Plot area (ha).

The termite-free usable volume (Vu) was calculated as:

$$Vu = Vt - Va$$

Where, Vt is the total stem volume and Va is the volume lost due to termite damage.

RESULTS AND DISCUSSION

Morphological and molecular identification

Based on the results of morphological identification, two termite families were obtained, namely Termitidae and Rhinotermitidae, from these two families, three termite genera were obtained, namely *Coptotermes*, *Nasutitermes*, and *Microcerotermes*. The genus *Microcerotermes* is characterized by a rectangular, monomorphic head shape, mandible edges (in the mandible) serrated from right to left, and antennae having 13 segments (Figure 2.A). *Coptotermes* is characterized by large body size (length ±1.41 mm and width ±0.76 mm), head ovate, longer than wide, narrow anteriorly, yellow-orange color, flat pronotum, mandible and no teeth and fontanella (Figure

2.B). *Nasutitermes* soldier caste appears to be characterized by the length and width of the body respectively ±1.91 mm and 1.32 mm, the pronotum is in the shape of a horse saddle, the head capsule has a modified conical to cylindrical rostrum, the head color is brownish yellow with brown rostrum, and the antenna consists of of 13 segments (Figure 2.C) (Tho 1992).

Based on molecular analysis using partial mitochondrial cytochrome oxidase II (COII) gene sequence, the samples matched the same genera identified morphologically. Three species were identified molecularly in representative termite samples, namely *C. sepangensis*, *M. havilandi* and *N. matangensis*. *Nasutitermes* genus sample has similarities with *N. matangensis* from Singapore with a bootstrap value of 100%, the *Microcerotermes* genus sample with *M. havilandi* with a bootstrap value of 99.9%, and the *Coptotermes* genus sample with *C. sepangensis* from Malaysia with a bootstrap value of 100%. The phylogenetic tree is displayed in Figure 3.

Coptotermes sepangensis, *M. havilandi* and *N. matangensis* reported by Jalaludin et al. (2018) is associated with oil palm stands in Pahang, Malaysia, although its status as a pest is unknown. As for *Coptotermes* reported by Syaukani et al. (2023), attacked cocoa plantations in Sumatra, Indonesia. These three species were first reported by Prastyaningsih et al. (2020) associated with *E. pellita* as a group of wood eaters. Proximately 3.1% of the *E. pellita* stands sustained damage caused by the termite *N. matangensis*, which creates holes in the trunks, inhibits tree growth, and can potentially cause tree mortality (Prastyaningsih 2024). In addition to morphological-based identification, molecular techniques for phylogenetic analysis and identification of termite groups associated with *E. pellita* are efficient strategies for analyzing the taxonomic position of termites. The large morphological differences between termite genera are often insufficient to distinguish traits at the species level. In some cases, termite phylogeny and taxa based on morphological character analysis even lead to significant contradictions as confirmed by Hellemans et al. (2024).

Termite infestation and wood loss

Termite infestation remained absent at age 1 year in both rotations (Figure 4). At age 2 years, some plots showed zero infestation, while other plots had small non-zero infestation. An increase in infestation is observed beginning at age 3, with peak levels occurring between ages 3 and 4. This pattern indicates that young stands were relatively resistant to termite attack, but their susceptibility increased with tree age. In 4th rotation, severity increased gradually with stand age, culminating at age 4 with a higher proportion of mild (21.5%) and moderate (7.89%) symptoms, along with severe cases (3.07%) and tree mortality (7.46%) (Figure 4.A).

In contrast, in the 5th rotation, the proportion of mild infestation was lower (level 1: 13.89-15.87%), while the proportion of dead infestation was higher (level 4: 12.30% at age 3 years), indicating that damage developed more rapidly and reached a greater intensity than in the 4th rotation. The infestation peak also occurred earlier, at the age of three years, suggesting that stands in the 5th rotation were more vulnerable to termite attack from an early age.

Some plots in the 5th rotation were located on sloped areas with high soil moisture, conditions that provide an ideal environment for termite development. In addition, the presence of termite nests and abundant organic debris on the soil surface may have accelerated the colonization process. The combination of these factors, unfavorable site conditions, pre-existing termite populations, and abundant organic matter contributed to the higher termite abundance observed in the 5th rotation.

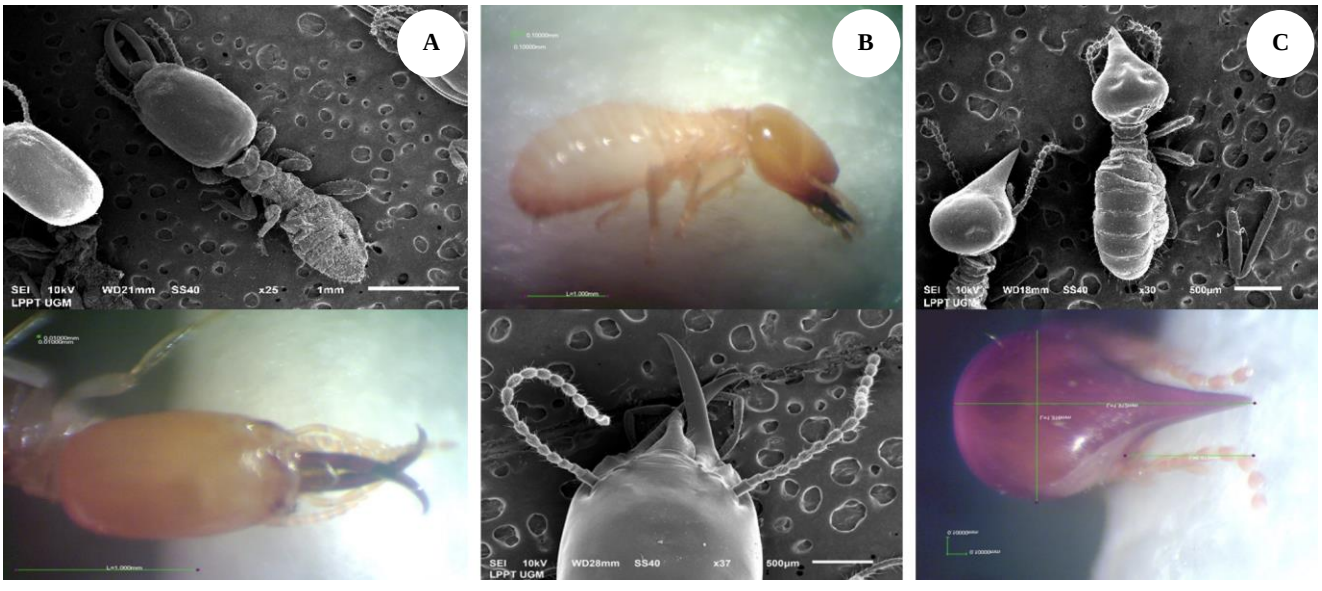

Figure 2. Morphological features of each termite genus. A. Bodies and head of the genus *Microcerotermes*, B. Bodies and heads of the genus *Coptotermes*, C. Bodies and head of *Nasutitermes*

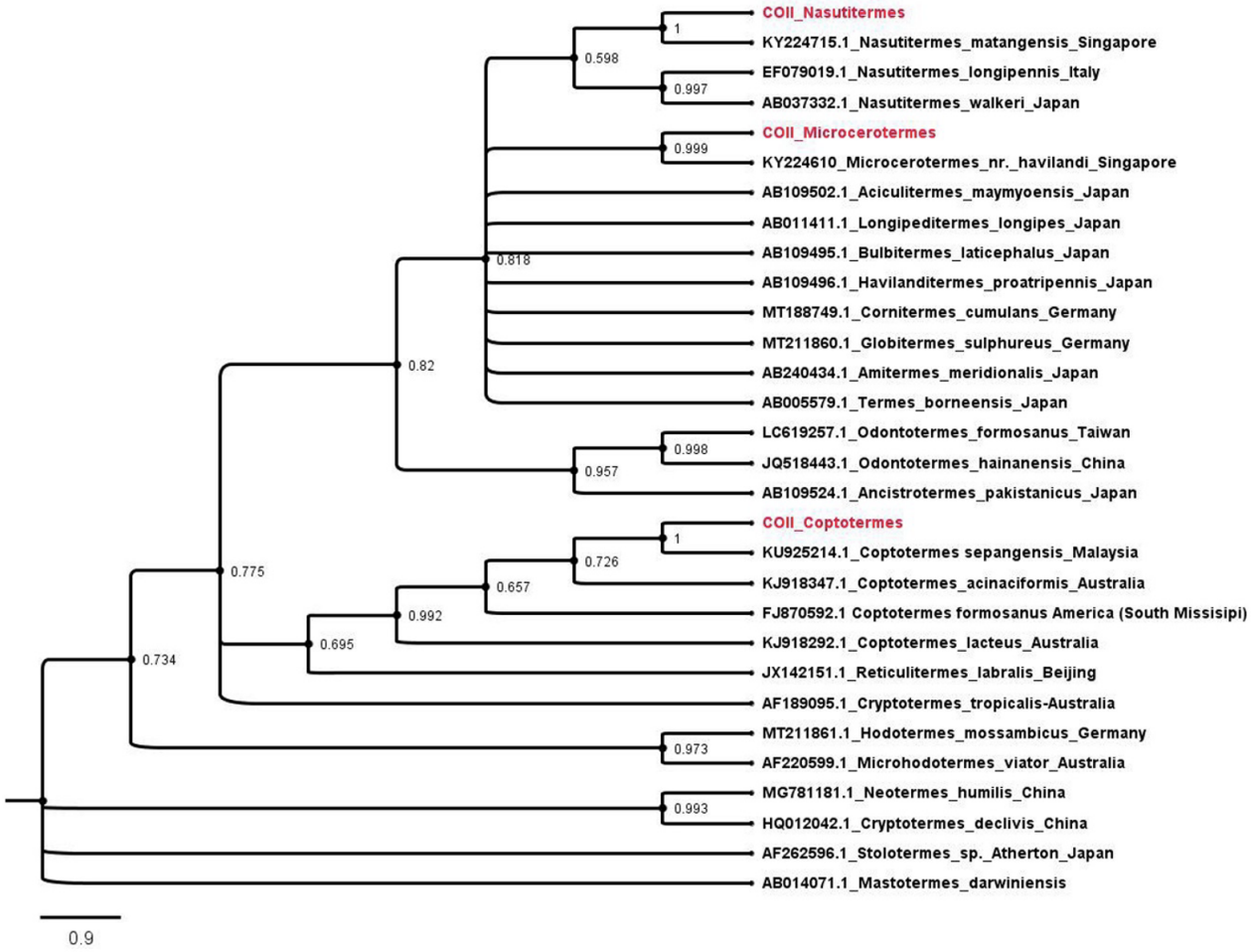

Figure 3. Molecular species identification based on the maximum likelihood tree using the COII gene marker. Bootstrap value with 1000 times replication above 50% available on nodes, *Mastotermes darwiniensis* was used as the outgroup. Species identified in this study are marked in red fonts. The scale bar indicates substitution per nucleotide position

Species frequency analysis showed that *Microcerotermes* was the most dominant genus, followed by *Nasutitermes* and *Coptotermes* (Figure 4.B). The bar charts indicated that in 4th rotation, *Microcerotermes* infestation peaked with a relatively high proportion of trees in both the "mild" (level 1: 18.0%) and "dead" (level 4: 6.1%) categories categories, whereas in the 5th rotation, *Microcerotermes* infestation reached its peak with a higher of trees in the "mild" (level 1: 10.3%) category and the "dead" (level 4: 9.5%). By contrast, *Nasutitermes* and *Coptotermes* infestations remained lower in both frequency and severity.

At the stand level, *Microcerotermes* infestation dynamics varied between rotations. The highest infestation was recorded in the 4th rotation at age 3 years. In contrast, in the 5th rotation, the maximum infestation occurred later, at age 4 years. These results suggest that both stand age and rotation strongly influence the abundance and severity of termite attacks, with the 5th rotations being more vulnerable to early and intense damage.

The differences in termite infestation patterns between the 4th and 5th rotations of *E. pellita* stands highlight the role of ecological and management factors in shaping the dynamics of attack. In the 4th rotation, the intensity of infestation (level 1: mild) was markedly higher, largely due to delay in implementing silvicultural practices, particularly in weed control and site cleaning. These management lapses created favorable microhabitats by allowing the accumulation of organic matter and understory vegetation, which in turn provided continuous resources and shelter for termite colonies. In contrast, the 5th rotation generally contained residual roots and stumps from previous cycles that served as potential substrates for colony establishment. The presence of deadwood and biomass residues is widely recognized to enhance termite populations, particularly those of the genus *Microcerotermes.*

The consistent dominance of *Microcerotermes* over *Nasutitermes* and *Coptotermes* across both rotations reflects its ecological and physiological advantage under Eucalyptus stand conditions. Recent evidence shows that *Microcerotermes* possesses specific traits and specialized gut microbiomes that enable efficient lignocellulose degradation (Xie et al. 2024). These adaptations allow it to exploit woody debris, litter, and root remnants from previous rotations, explaining its prevalence in mid- to late-rotation stands. In contrast, *Coptotermes*, although known

as an aggressive soil-feeding termite (Chouvenc 2025), was less dominant in this study, likely due to edaphic or moisture conditions that constrained colony development.

In addition, the higher severity of infestation observed in the 5th rotation, particularly at three years of age with mortality reaching 9.3%, may be related to stand age and wood quality. Younger stands are characterized by lower lignin and higher starch content, which can provide favorable nutritional resources for termites (Xie et al. 2024). This indicates that rotation cycles influence not only the productivity of *Eucalyptus* stands but also their vulnerability to biotic disturbances. Consequently, effective management of residual biomass—particularly stumps, roots, and litter from previous rotations—together with early monitoring during the initial stages of infestation should be integral to an Integrated Pest Management (IPM) approach. Such measures are essential to reduce termite colonization, prevent escalation into severe or mortality categories, and maintain long-term productivity of *E. pellita* plantations.

Overall, these findings demonstrate that termite infestation severity in *E. pellita* plantations results from a complex interplay among stand age, host condition, and the availability of substrates from residual biomass. Therefore, classifying severity levels is not only essential for describing the extent of damage but also serves as a critical foundation for management strategies. Specifically, managing residual biomass, particularly stumps and litter at the end of the rotation, together with early monitoring at the initial stages of infestation should be integral components of an integrated pest management approach to prevent escalation to severe or mortality levels.

Termite attack can be seen on the stem in the form of skin damage to the sapwood. Termite nests appear on the surface of the skin to cover the entire tree trunk. In addition, the stems look porous and have holes, several trees were also found dead. Wood-feeders termite causes serious damage to *Eucalyptus* by hollowing out stems, especially in old stands, causing decline and dieback of the trees (Figure 5). Wood-feeders start feeding on the basal portions of logs and can destroy the entire log in just a few months. According to Alamu and Ewete (2023), wood with greater age tends to be harder, and increased hardness is associated with higher termite damage intensity.

In addition, the passage ways made by termites physically cause the stem to suffer damage to the outer skin and spread into the stem tissue. Gallio et al. (2020) explained that wood deterioration by termites also reduces the content of cellulose, hemicellulose, and lignin in wood. This process, According to Farhan et al. (2021), the digestive system of termites, enriched with symbiotic microorganisms, enables efficient lignocellulose breakdown, further exacerbating wood decay and nutrient loss.

Table 2 illustrates the impact of termite infestation on the usable wood volume of *E. pellita* plantations in 4th rotation and 5th rotation. At 1 year of age (U1), no wood loss was recorded at either site, indicating that young stands were not yet affected. As the trees matured, wood loss began to occur and exhibited distinct patterns between the two locations. In 5th rotation, the highest wood volume loss occurred at 3 years of age (U3), with 7.54 m³/ha of wood lost, corresponding to 9.10% reduction. In contrast, 4th rotation recorded its greatest wood volume loss at 4 years of age (U4), totaling 7.10 m³/ha with 5.53% reduction. When considering the total stand volume, the proportion of wood volume loss was higher in 5th rotation at the peak of infestation, whereas in 4th rotation, the loss accumulated progressively in older trees. These trends highlight the site-specific dynamics of termite induced wood loss, with 5th rotation experiencing earlier volume reduction and 4th rotation exhibiting greater cumulative loss toward the end of the rotation.

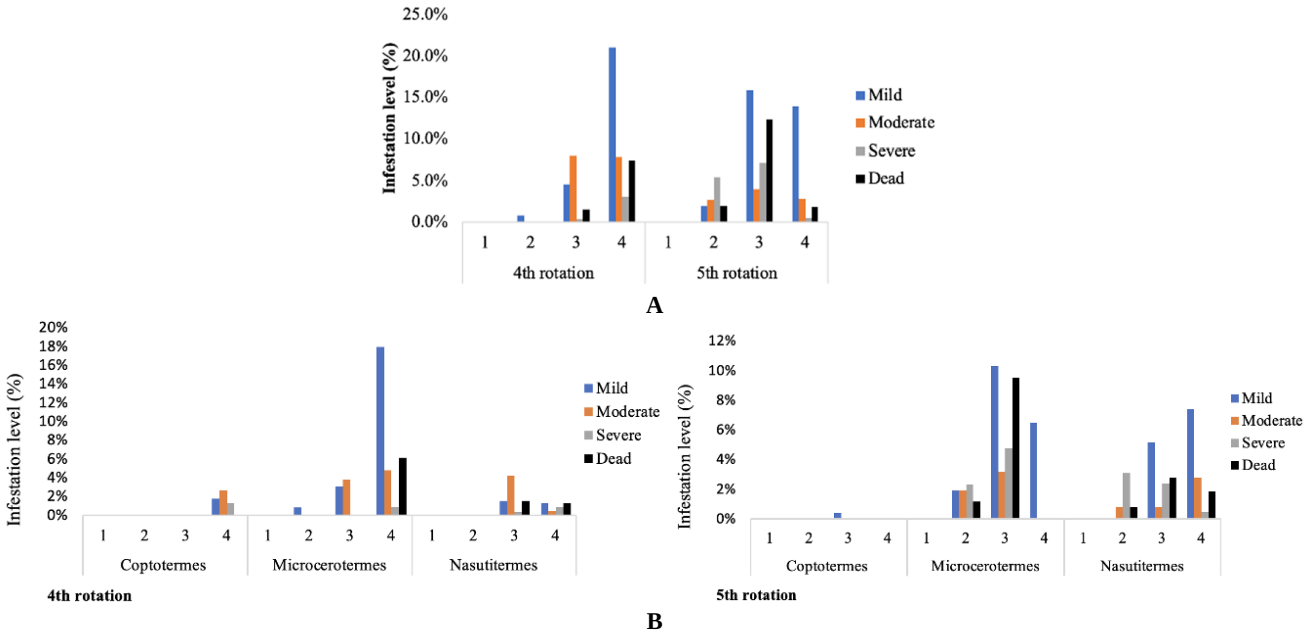

Figure 4. A. Percentage of termite infestation in *Eucalyptus pellita* based on stand age in rotation and plot, B. Relative frequency of termite genera infesting *E. pellita*

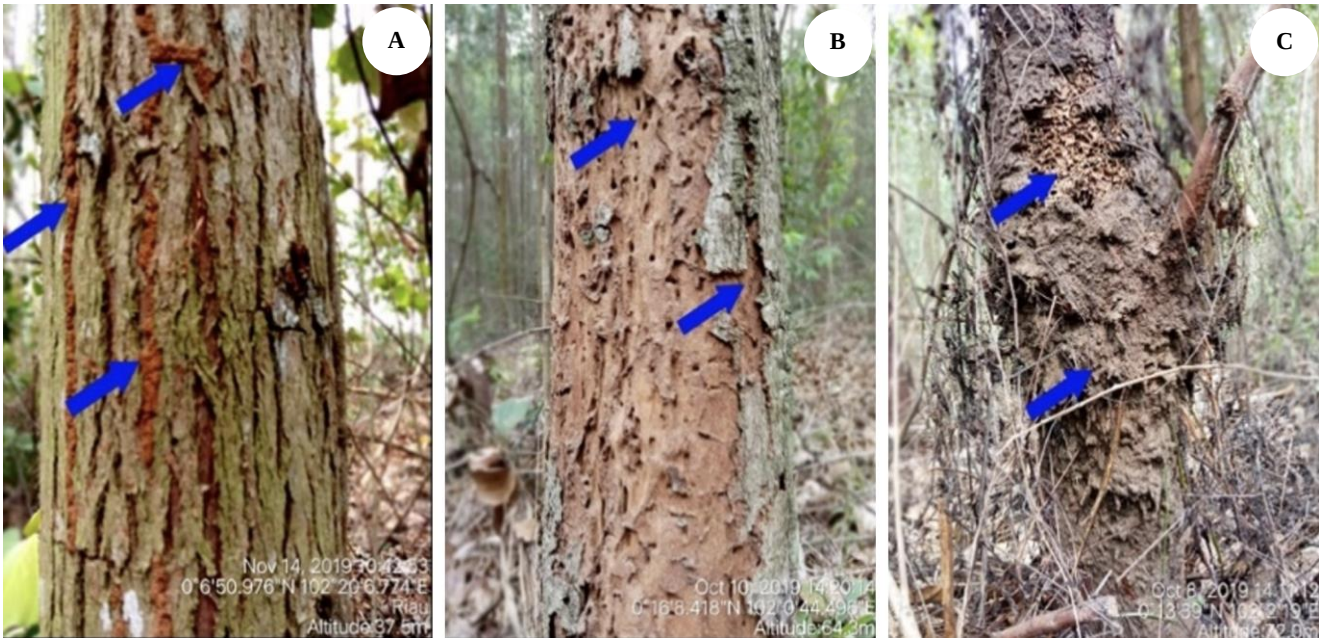

Figure 5. Stem damage on *Eucalyptus pellita* stands. A. Termite travel passages, B. Hollowed, weathered and porous stems, C. Termite nests on the stems

Table 2. The impact of termite infestation on usable volume of *Eucalyptus* trees (m^3/ha)

Information	Unit	4th rotation				5th rotation			
		U1	U2	U3	U4	U1	U2	U3	U4
Tree volume total ≥5 cm	m^3/ha	17.93	51.13	109.45	128.35	14.64	36.61	82.80	110.27
Termite infested volume total	m^3/ha	-	0.04	2.57	7.10	-	0.81	7.54	3.07
Usable volume total	m^3/ha	17.93	51.08	106.87	121.25	14.64	35.80	75.27	107.20
Percentage of termite infestation	%	0.00	0.09	2.35	5.53	0.00	2.27	9.10	2.78

Notes: U1: 1-year-old tre, U2: 2-year-old tree, U3: 3-year-old tree, U4: 4-year-old tree

Compared to the total stand volume, the proportion of wood affected by termites increased with tree age, reaching a peak of 5.53% at 4 years in 4th rotation and 9.10% at 3 years in 5th rotation, according to Table 2. This suggests that, although termite attack peaked earlier in 5th rotation, the cumulative impact across the rotation remained moderate, with 4th rotation showing a progressive increase toward the later stage. Termite colonies are capable of spreading across stands, attacking multiple trees within a radius, and causing internal trunk damage that reduces usable wood volume. Despite these losses, overall plantation productivity was not severely disrupted, as total damage remained below 5% of stand volume. This relatively moderate disturbance can be attributed to the intensive silvicultural practices and pest management strategies employed in monoculture plantation systems.

Ecologically, the earlier peak of infestation in the 5th rotation indicates that stand vulnerability is strongly influenced by site conditions such as microclimate, soil properties, and residual biomass from previous rotations, which may facilitate faster colony establishment (Allman et al. 2023; Jonge et al. 2024; Klein et al. 2025; Udali et al. 2025). The higher cumulative loss in 4th rotation emphasizes the importance of stand age, as older stands provide longer time frames and more substrate for termite proliferation (Boulogne et al. 2017; Prastyaningsih et al. 2020). The consistent presence of *Microcerotermes* across both sites further supports the role of wood-feeding termites in exploiting residual biomass and contributing to cumulative damage (Griffiths et al. 2019).

From an economic perspective, even a 7.10-7.54 m^3/ha reduction in usable wood volume represents a non-trivial loss when extrapolated across large *E. pellita* plantations (Beckline et al. 2016; Kalleshwaraswamy et al. 2022; Kim and Chung 2022). Assuming an average wood density of 0.45-0.50 g/cm^3 for *E. pellita* (Hardiyanto et al. 2021), these losses correspond to approximately 3.2-5.0 tons of dry biomass per hectare. Given that this biomass is directly linked to pulp yield, reductions of this magnitude can decrease fiber supply, lower mill efficiency, and increase raw material costs. While the percentage loss may appear moderate at the plantation scale, in industrial contexts such impacts can accumulate into significant economic losses, particularly when occurring consistently across multiple rotations.

Eucalyptus production was not seriously disturbed by termite attack although losses of up to 9.10% were recorded. This condition still relative minor distribution because this monoculture tree plantation system has good pest control management and intensive silviculture. Notably, *Coptotermes curvignathus* has been reported to infest both healthy and declining trees, often leading to extensive heartwood degradation. In addition, Gallio et al. (2020) reported a wood mass loss of 66.88% caused by *Nasutitermes* spp., on *Eucalyptus grandis*, particularly in wood with a density of 412 kg/m³ at 12% moisture content, highlighting the destructive potential of termite infestations in forest plantations.

The genus *Nasutitermes* is among the most abundant wood-feeding Termitidae and an extremely diverse and heterogeneous group in terms of its biogeography and morphology (Boulogne et al. 2017). *Nasutitermes* nests were found in observation plots in hill areas with arboreal nest types associated with wood or tree nesting, either in living or dead trees. Termites nest in wood because they can easily access cellulose and use it as a resources to expand the their nest. Prastyaningsih et al. (2020) stated that *Nasutitermes* is an arboreal and subterranean termite that builds nests in tree trunks and branches. The lifestyle and attacks of each species studied in this study can be further investigated to form the basis for future termite control strategies for *E. pellita*. Control through appropriate cultivation techniques, micro-climate management, biological agents, or insecticidal active ingredients is a management strategy whose effectiveness can be assessed in controlling wood-eating termites in *E. pellita*, especially the species identified in this study. Thus, the outbreak of pest attacks can be prevented, further losses can be minimized, and the supply of paper and pulp will remain stable in the future.

In conclusion, *E. pellita* tree plantation in Riau experienced relatively low levels of termite infestation and wood volume loss. The highest infestation was recorded in 4th rotation at age 3 years (U3) with up to 9.10% of the tree volume affected (equivalent to 7.54 m^3/ha), while in 5th rotation the maximum loss reached 7.10 m^3/ha at age 4 years (U4). Three termite species were identified as pests infesting *E. pellita*, namely *C. sepangensis*, *M. havilandi* and *N. matangensis* based on morphological characteristics and molecular COII gene analysis. These findings highlight the importance of regular monitoring and the implementation of effective pest management strategies to minimize termite-related wood loss and ensure stable production in monoculture plantation systems.

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