Potential Use of Three Meliaceae Species as Alternative Timber Resources in Tropical Regions: Biological Performance and Mechanical Properties

Kazushi Nakai [a,b,*]

Fast-growing species have potential as alternative timber species for sustainable wood utilization in tropical regions. This study evaluated the biological performance and mechanical properties of three Meliaceae species: *Swietenia macrophylla*, *Toona ciliata*, and *Azadirachta indica*. Resistance to subterranean termites and wood-decay fungi was assessed in accordance with Japanese Industrial Standards (JIS). In addition, Brinell hardness and bending properties were measured. All three species showed high resistance to termite attack; however, decay resistance was species dependent. *S. macrophylla* and *T. ciliata* exhibited relatively high resistance to both white-rot and brown-rot fungi, whereas *A. indica* showed high mass loss despite having comparable density to the other species. The fungal susceptibility of *A. indica* could not be explained by density or hardness alone and was likely associated with differences in chemical durability including extractive composition. *T. ciliata* showed mechanical properties comparable to those of *S. macrophylla*, a high-value timber widely used in various applications. These results indicate that *T. ciliata* has strong potential as an alternative timber resource in tropical regions. Its biological performance and mechanical properties may support sustainable wood utilization and diversified local land-use systems.

DOI: 10.15376/biores.21.3.6960-6974

Keywords: Meliaceae; Swietenia macrophylla; Toona ciliata; Azadirachta indica; Termite resistance; Decay resistance; Mechanical properties; Tropical timber resources

Contact information: a: Research Institute for Sustainable Humanosphere, Kyoto University, Gokasho, Uji, Kyoto, 6110011, Japan; b: Yamaha Corporation, 10-1, Nakazawa, Chuo-ku, Hamamatsu, 4308650, Japan;
** Corresponding author: nakai.kazushi.2m@kyoto-u.ac.jp*

INTRODUCTION

In tropical regions, biological deterioration caused by subterranean termites and wood-decay fungi is a major concern in developing timber utilization. Resistance to such organisms is therefore one of the most critical properties determining the durability and service performance of wood used in both interior and exterior environments, particularly in structural and other applications where long-term durability is required (Okanlawon *et al.* 2020). Reliable evaluation of biological performance is therefore important for identifying timber species suitable for sustainable utilization under tropical climatic conditions.

Tanzania, located in East Africa, is widely covered by Miombo woodland, which supports several durable native timber species such as *Dalbergia melanoxylon* (African blackwood), *Pterocarpus angolensis*, and *Afzelia quanzensis*. They are traditionally recognized as valuable timbers. *D. melanoxylon* has been one of the most valuable timber species in musical instruments industry. Both *P. angolensis* and *A. quanzensis* have been locally valuable due to their high density and resistance to biological deterioration (Nakai and Yoshimura 2020). However, rapid economic growth with urban development since the early 2000s has increased the demand for large-diameter timber, leading to intensive harvesting in domestic forests (Itani 2023). Simultaneously, expansion of agricultural land, including shifting cultivation for cash crops such as sesame, has accelerated forest degradation and deforestation (Doggart *et al.* 2020; Nakai 2025). The economic loss associated with deforestation in Tanzania has been estimated to reach approximately 273 billion Tsh (about 171 million USD) between 2013 and 2023 (UNEP 2015). Securing alternative timber resources capable of supporting both wood production and local land-use has therefore become an urgent challenge.

Timber species belonging to the family Meliaceae have attracted attention as potential alternative resources. Several Meliaceae species, including *Swietenia macrophylla* (big leaf mahogany) and *Entandrophragma cylindricum* (sapelle), have been utilized as high-value timbers for furniture and musical instruments. Many species in this family are regarded as fast-growing tree species, and some Meliaceae species have been reported to attain mean annual volume increments of approximately 15 to 20 m^3/ha under suitable conditions (Krisnawati *et al.* 2011; Praciak *et al.* 2013). These species have been recognized as useful tropical timber or multipurpose trees and have been planted or introduced widely under tropical and subtropical conditions (da Mota Porto *et al.* 2025; Krisnawati *et al.* 2011; Praciak *et al.* 2013). The rapid growth enables mid-term timber production cycles of approximately 10 to 30 years, making them suitable candidates for plantation forestry and agroforestry systems. For example, *S. macrophylla* has been widely planted throughout tropical regions as a component of reforestation and afforestation programs, including in South-east Asia, tropical Africa, Central America, and the southern Amazon basin, and has been valued for both commercial timber production and multipurpose land use (Praciak *et al.* 2013). *Azadirachta indica* (Neem) has also been widely introduced throughout tropical regions and recognized as a multipurpose species, providing both timber and non-timber forest products such as neem oil based on a natural chemical component, azadirachtin, extracted from seeds (Kurimoto *et al.* 2014; Gupta *et al.* 2017). In Tanzania, *A. indica* is commonly planted as an urban and roadside tree. In addition, several Meliaceae species, including *Toona ciliata*, have been introduced to East Africa to support land restoration and timber production in dry tropical environments.

In contrast, available information on *T. ciliata* remains limited compared with that on *S. macrophylla* and *A. indica*. *Toona ciliata* (Toona) has been regarded as a valuable timber species in China, and it is commonly known as Chinese mahogany (Mao *et al.* 2021). The species was also introduced to Tanzania in the early 20th century and is currently distributed in several regions including Kilimanjaro, Kigoma, and Morogoro (Itani 2023). This species exhibits relatively rapid diameter growth, with mean annual increments ranging from approximately 0.2 to 2.0 cm (Bhattacharyya *et al.* 1992; Heinrich and Banks 2006). Although it has been used locally as a structural timber, large-scale plantation efforts have been limited due to the short viability of seeds and low germination rates (Itani 2023). Nevertheless, the wood shows visual and anatomical similarities to mahogany, and it is sometimes traded as a high-value timber. These characteristics suggest that *T. ciliata* may serve as a promising candidate species for alternative timber use in tropical regions, including East Africa.

Despite the recognized potential of Meliaceae species as multipurpose timber resources, comparative information on their resistance to biological deterioration under tropical conditions remains limited. In particular, systematic evaluation of durability against both subterranean termites and wood-decay fungi is necessary to assess their suitability as alternative timber resources in tropical dry regions. In this study, three Meliaceae species were selected: *S. macrophylla*, a well-established high-value timber; *A. indica*, a multipurpose species widely introduced in tropical regions; and *T. ciliata*, a candidate alternative timber species with potential for local use in East Africa. The objective of this study was to evaluate their biological performance against subterranean termites and wood-decay fungi and to compare their performance with those of representative native Tanzanian timber species, including *Dalbergia melanoxylon*, *Pterocarpus angolensis*, and *Afzelia quanzensis*, based on results reported previously under comparable test conditions (Nakai and Yoshimura 2020). In addition, basic mechanical properties, including bending properties and hardness, were assessed to examine their potential for timber utilization. The novelty of the present study lies in the practical comparative evaluation of three important Meliaceae species under a common experimental framework, integrating biological performance with basic mechanical properties relevant to timber utilization in tropical regions. The results provide fundamental information for selecting timber species suitable for sustainable forest utilization and diversified land-use systems in tropical regions.

EXPERIMENTAL

Wood Specimens

Three Meliaceae species, *Swietenia macrophylla*, *Azadirachta indica*, and *Toona ciliata*, were used in this study. Logs of each species were collected in Karnataka and Kochi, southern India, and sawn by local sawmills into 30 flat-sawn boards measuring 1000 mm (L: longitudinal) × 25 mm (R: radial) × 90 mm (T: tangential) for each species. The boards were obtained from each heartwood, and they were also air-dried to an approximate moisture content of 20% before shipping to Japan. Upon arrival in Japan, two boards from each species were randomly selected as sample boards for monitoring moisture content. Initial moisture content was determined based on oven-dry weight after drying at 105 °C for more than 24 h. For each sample board, a small specimen measuring 20 mm (L) × 20 mm (R) × 20 mm (T) was prepared from a position 30 mm inward from the longitudinal end of the board, and its oven-dry weight was measured. After measurement of the initial moisture content, all boards were air-dried indoors for more than one month. When the moisture content of all sample boards had decreased below 15%, kiln drying was conducted to further reduce the moisture content of all boards.

The kiln-drying schedule was identical for all boards. In the first step, the boards were dried at 65 °C and 33% relative humidity (RH) for 14.5 h. In the second step, they were dried at 70 °C and 27% RH for 48 h. In the final step, the boards were conditioned at 75 °C and 63% RH until the moisture content of all sample boards was adjusted to approximately 10% (Table 1). After kiln-drying, all boards were conditioned at 22 °C and 60% RH for more than one month. Test specimens for all subsequent tests were then prepared from multiple randomly selected boards among the remaining 28 boards of each species, according to the dimensions required for each test. All specimens were visually confirmed to be free of defects before testing. For the biological durability tests (termite test and decay test), air-dried sapwood specimens of a Japanese species, *Cryptomeria japonica*, were used as controls, as specified in JIS K 1571 (2010). The control specimens were used to verify that termite feeding activity and fungal decay activity were sufficient for valid evaluation under the test conditions. The prepared *C. japonica* specimens were also conditioned at 22 °C and 60% RH for more than one month before testing.

Table 1. Schedule of Kiln-Drying for Wood Boards

Step	Temperature (°C)	RH %	Duration* (h)	Target MC %	Average MC** %
1	65	33	14.5	<10	9.2
2	70	27	48	<5.5	5.3
3	75	63	72	6.5-7.5	7.7

* The duration was determined when the average MC reached the target MC
** This parameter was calculated from the actual weights of the sample boards

Termite Test

The termite test, a no-choice feeding test, was conducted in accordance with JIS K 1571 (2010) using the subterranean termite *Coptotermes formosanus*. A test specimen measuring 20 mm (L) × 10 mm (R) × 10 mm (T) was placed on a plastic sheet at the bottom of a cylindrical acrylic container (80 mm in external diameter and 60 mm in height) with a plaster base. A total of 150 mature workers and 15 soldiers, collected from a laboratory colony maintained in the Deterioration Organisms Laboratory (DOL) at the Research Institute for Sustainable Humanosphere, Kyoto University, were introduced into each test container. Five replicates were prepared for each species. The containers were placed on water-soaked cotton in a dark chamber maintained at 28 ± 2 °C and more than 80% RH for 3 weeks. Mass loss of the specimens was calculated as the difference between oven-dry weights before and after the test, after drying at 60 ± 2 °C for 48 h. The wood consumption rate (WCR) was calculated as the amount of wood consumed per worker termite per day, based on specimen weight loss and termite mortality (Nakai and Yoshimura 2020). WCR was calculated using Eq. 1,

$$WCR = W_L \int_0^P \left[\left(\frac{N_S - N_I}{P}\right) x + N_I\right] dx \quad (1)$$

where W_L is the mass loss of wood specimen (μg), P is the test period (3-week), N_S is the initial number of workers (150 workers), N_L is the number of survived workers.

Decay Test

The decay test was conducted in accordance with JIS K 1571 (2010). Test specimens measuring 10 mm (L) × 10 mm (R) × 20 mm (T) were prepared from each board. Three specimens were exposed to a monoculture of either *Trametes versicolor* (COV), a white-rot fungus (FFPRI 1030), or *Fomitopsis palustris* (TYP), a brown-rot fungus (FFPRI 0507), in glass jars and incubated in a dark chamber maintained at 26 ± 2 °C for 12 weeks (Nakai and Yoshimura 2020). Three jars were prepared for each fungal species, resulting in 9 replicates for each wood species. Percent mass loss of each specimen was calculated according to the same procedure described for the termite test. Specimen weights were measured after drying at 60 ± 2 °C for 48 h before and after the test.

Wood Hardness

Wood surface hardness was evaluated as Brinell hardness in accordance with JIS Z 2101 (2009) using a Brinell hardness tester (Tokyo Koki Testing Machine Co. Ltd., Kanagawa, Japan). For each species, three specimens measuring 40 mm (L) × 25 mm (R) × 40 mm (T) were prepared from the boards. Prior to testing, the specimens were conditioned at 22 °C and 60% RH for more than one week. Brinell hardness was measured on the transverse, radial, and tangential surfaces of each specimen. For each surface, measurements were taken at three different points, and the mean value was regarded as the hardness of that surface for each specimen (Fig. 1). After the specimen was set in the testing machine, a steel ball with a diameter of 10 mm was pressed into the surface, and the load at an indentation depth of 1/π mm (approximately 0.32 mm) was recorded. Brinell hardness was calculated from the applied load and the diameter of the indentation according to Eq. 2,

$$Brinell\ Hardness = \frac{9.8P}{10} \tag{2}$$

where P (N) is the maximum load when the indentation depth reached 1/π mm. 1 kg was estimated at 9.8 N in this calculation.

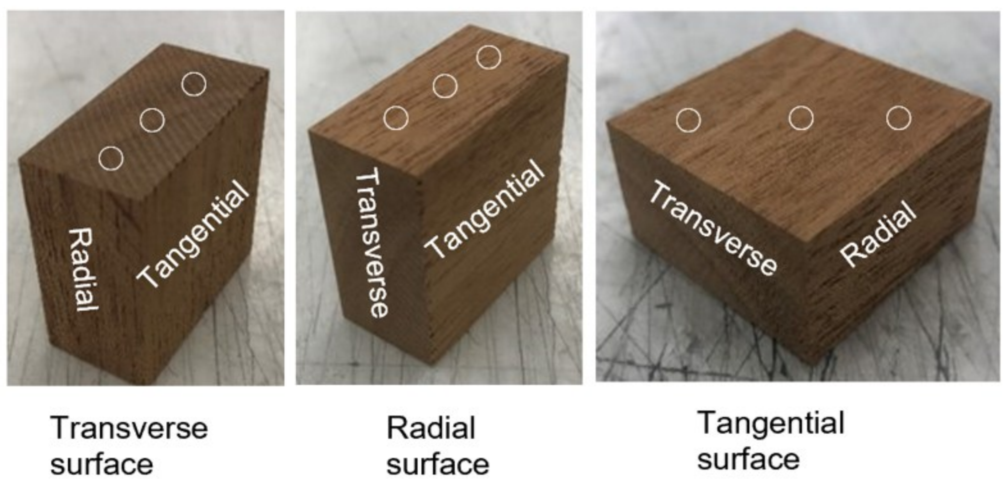

Fig. 1. Example of hardness measured points on each surface (*T. ciliata*)

Bending Properties

The bending properties of each species were evaluated using a universal testing machine (Instron 5582, Instron Co., MA, USA). Test specimens measuring 330 mm (L) × 20 mm (R) × 20 mm (T) were prepared from the boards of each species, and five specimens were tested for each species. Prior to testing, the specimens were conditioned at 22 °C and 60% RH for more than one week. A three-point bending test was conducted with a span length of 280 mm using cylindrical supports with a radius of 10 mm. A static load was applied at the center of the span using a cylindrical loading head with a radius of 15 mm at a loading speed of 5 mm/min, and the load-deflection curve was recorded. The slope (K) of the linear elastic region was determined by linear regression using at least four data points within the proportional limit of the load-deflection curve. The bending modulus of elasticity (MOE) was calculated from Eq. 3 using K and the second moment of area,

$$MOE = \frac{K \cdot L^3}{4bh^3} \tag{3}$$

where L is the span length (280 mm), b (mm) is the width of the specimens, h (mm) is the thickness of the specimens. The width was defined as the radial dimension, and the thickness was defined as the tangential dimension of the specimens in this test. The failure load was defined as the point at which the first visible crack appeared on the surface opposite to the loading point and the applied load began to decrease. The modulus of rupture (MOR) was calculated using Eq. 4,

$$MOR = \frac{3LP}{2bh^2} \quad (4)$$

where L is the span length (280 mm), P (N) is the failure load, b (mm) is the width of the specimens, and h (mm) is the thickness of the specimens.

Statistical Analysis

All data are presented as mean ± standard deviation (SD). Statistical differences among species for each measured property were evaluated by one-way analysis of variance (ANOVA), followed by the Tukey-Kramer multiple comparison test at the 5% significance level ($p < 0.05$). All statistical analyses were performed using BellCurve for Excel (Social Survey Research Information Co., Ltd., Tokyo, Japan).

RESULTS AND DISCUSSION

Biological Performance against Termite and Wood Decay Fungi

Table 2 shows the air-dried densities, mass losses and wood consumption rates (WCRs) obtained in the termite test. The air-dried densities of the three Meliaceae species, *S. macrophylla*, *T. ciliata*, and *A. indica* were 0.51 g/cm^3, 0.53 g/cm^3, and 0.56 g/cm^3, respectively, with no significant differences among them. These values were significantly higher than that of the control, *C. japonica*, and were approximately 1.8 times higher than the control. They were lower than the air-dried densities reported for highly durable native Tanzanian species, the heartwoods of *D. melanoxylon*, *P. angolensis*, and *A. quanzensis*, in a previous study (Nakai and Yoshimura 2020). Mass loss and WCR were not significantly different among the three Meliaceae species (Table 2). In the control specimens, the mass loss reached 298.4 mg after the test period, and the WCR was 98.0 µg/worker/day. These values indicate that termite feeding activity was sufficient during the test period. In a previous study, the corresponding values for the control were 178 mg (mass loss) and 63.8 µg/worker/day (WCR) (Nakai and Yoshimura 2020), suggesting that termite activity in the present test was comparable or higher.

Table 2. Specimens' Densities and Wood Consumption by the Termites during the Test Period (mean ± SD)

Species Name	Air-dried Density (g/cm^3)*	Mass Loss (mg)*	WCR (µg/worker/day)*
Swietenia macrophylla	0.51 ± 0.04^a	33.70 ± 23.07^c	11.58 ± 7.50^e
Toona ciliata	0.53 ± 0.02^a	25.70 ± 11.34^c	8.93 ± 4.06^e
Azadirachta indica	0.56 ± 0.14^a	28.90 ± 7.26^c	9.63 ± 2.53^e
Cryptomeria japonica	0.32 ± 0.03^b	298.40 ± 53.32^d	98.02 ± 18.12^f

* Mean values with the same letter are not significantly different according to the Tukey-Kramer test
($p > 0.05$).

The mortality rates of worker and soldier termites after 3-week test are shown in Fig. 2. The mean mortality rates of the control were 6.5% (worker) and 4.7% (soldier) respectively. All tested Meliaceae species showed significantly higher mean mortality rates of soldiers than that of the control, 74.7% (*S. macrophylla*), 84.0% (*T. ciliata*) and 80.7% (*A. indica*). In contrast, worker mortality showed a different pattern. The mean worker mortality rates were 15.2% for *S. macrophylla*, 16.2% for *T. ciliata* and 8.7% for *A. indica*. Although worker mortality in *S. macrophylla* and *T. ciliata* was significantly higher than that in the control, *A. indica* did not differ significantly from the control. However, worker mortality in *A. indica* was statistically similar to that in *S. macrophylla*, while *T. ciliata* showed significantly higher worker mortality than *A. indica* ($p < 0.05$). The results indicate that the tested Meliaceae species had high resistance to termite feeding. However, the relatively low worker mortality compared with soldier mortality suggests that their effect was not strongly insecticidal but was more likely related to feeding behavior or reduced palatability. Because no significant differences in air-dried density were observed among the tested Meliaceae species in the termite test (Table 2), the differences in termite resistance observed in this study were not interpreted as primarily density-dependent. Overall, the termite resistance of these species was comparable to that of highly durable native Tanzanian native species such as *D. melanoxylon* and *P. angolensis* (Nakai and Yoshimura 2020).

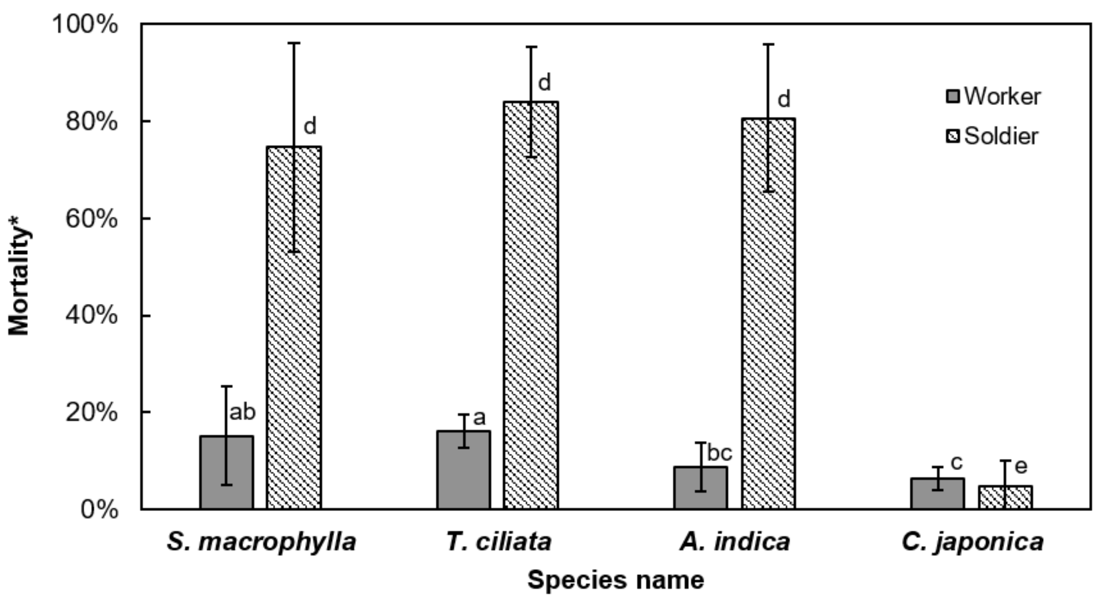

Fig. 2. Mortality rates of the workers and soldiers after 3-week no-choice feeding test with *Coptotermes formosanus* (mean ± SD) (n = 5). Note: * Mean values with same letter are not significantly different among wood species within each group (worker or soldier) according to the Tukey-Kramer test (p > 0.05)

Table 3 shows the air-dried densities of the specimens used in the decay test. The densities of *T. ciliata* and *A. indica* were not significantly different, whereas the density of *S. macrophylla* was lower than the other two species. All tested Meliaceae species had higher densities than the control (*C. japonica*). The density values in the decay test differed slightly from those in the termite test because separate specimen sets were prepared for each test from multiple randomly selected boards.

Figure 3 shows the percent mass loss of each species after 12 weeks of exposure to *Trametes versicolor* (COV) and *Fomitopsis palustris* (TYP). For COV, the mass losses of *S. macrophylla* and *T. ciliata* were 14.3% and 13.4% respectively and were significantly lower than that of the control ($p < 0.01$). These two values were statistically similar (p =

0.993). In contrast, *A. indica* showed a significantly higher mass loss than the other two Meliaceae species, reaching 52.6%. This value was also higher than that of the control, which showed a mass loss of 38.7% ($p < 0.01$). For TYP, the mass losses of *S. macrophylla* and *T. ciliata* were also lower than those of *A. indica* and the control. The mean mass loss of *S. macrophylla* was slightly negative (-2.3%), indicating that no measurable degradation occurred during exposure to TYP under the present test conditions. This slightly negative value was considered to reflect minor differences in specimen moisture condition before and after the test. In contrast, *A. indica* showed a mass loss of 15.9%, which was significantly higher than those of *S. macrophylla* and *T. ciliata* and statistically similar to that of the control (21.0%).

Table 3. Air-dried Densities of the Specimens Exposed to Decay Test (mean ± SD)

Species Name	Air-dried Density (g/cm^3)*
Swietenia macrophylla	0.48 ± 0.01[a]
Toona ciliata	0.58 ± 0.01[b]
Azadirachta indica	0.55 ± 0.11[b]
Cryptomeria japonica	0.33 ± 0.01[c]
* Mean values with the same letter are not significantly different following Tukey-Kramer test ($p > 0.05$).	

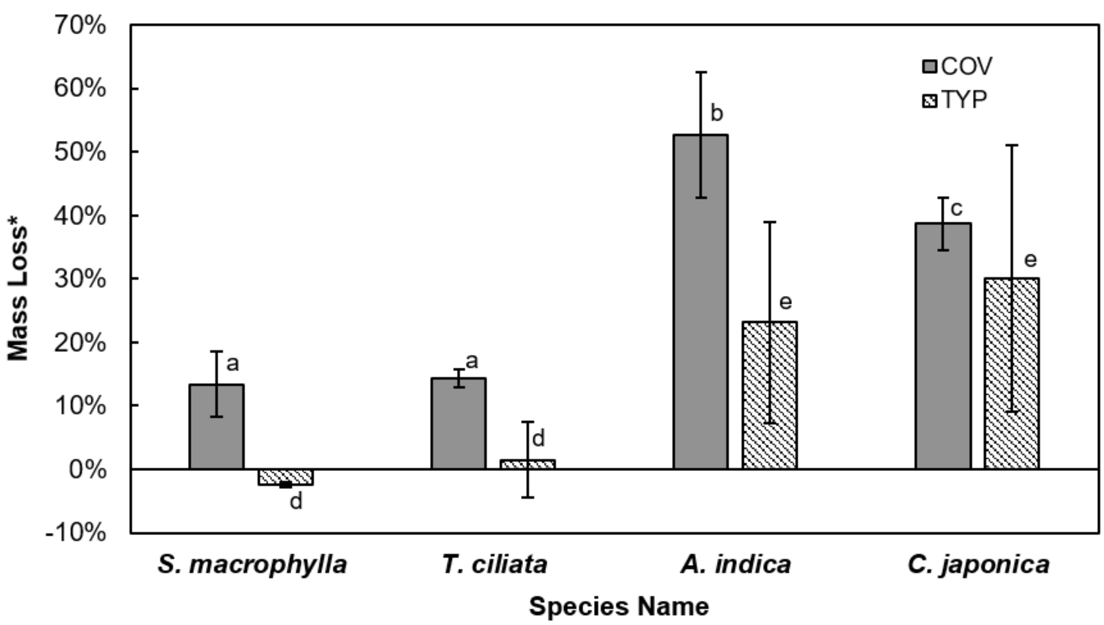

Fig. 3. Mass loss percentages of the tested wood specimens after 12-week exposure to COV and TYP (mean ± SD) (n = 9). Note: * Mean values with same letter are not significantly different among wood species within each group (COV or TYP) according to the Tukey-Kramer test ($p > 0.05$).

Overall, the termite and decay tests showed contrasting patterns. All three Meliaceae species exhibited high resistance to termite attack, comparable to that of durable native Tanzanian timbers such as *D. melanoxylon* and *P. angolensis*, which showed low mass loss and generally low worker mortality under comparable test conditions (Nakai and Yoshimura 2020). However, decay resistance differed markedly among species. *S. macrophylla* and *T. ciliata* showed relatively high resistance to both white-rot and brown-rot fungi, whereas *A. indica* was highly susceptible to fungal decay, particularly to white-rot fungus.

In general, both termite resistance and decay resistance are influenced by wood density and chemical durability. Previous studies have reported that mass loss tended to decrease with increasing wood density under field exposure conditions (Acanakwo *et al.* 2019), and that wood decay progressed more slowly in high-density species than in low-density species (Cambers *et al.* 2000). In the present study, however, air-dried density did not differ greatly among the three tested Meliaceae species. Therefore, the lower decay resistance of *A. indica* could not be explained by density alone.

Differences in chemical durability are likely to have contributed to the observed variation in decay resistance. Biological activities of compounds extracted from wood, leaves, seeds and other tree parts have been widely reported (Ohmura *et al.* 2000; Machado *et al.* 2013; Tascioglu *et al.* 2013). Neem oil extracted from *A. indica* seeds and wood contains biologically active compounds, including azadirachtin and limonoids (Kraus 1995). However, their antifungal effects might be weaker than their antifeedant effects against termites. Machado *et al.* (2013) reported that treatment of *Pinus radiata* wood with a 1% neem oil solution reduced mass loss caused by termite feeding but did not improve resistance to either white-rot fungi or brown-rot fungi. The present results are consistent with this tendency, although direct chemical analysis would be required to confirm whether differences in extractive composition contributed to the lower decay resistance of *A. indica*. Such differences may also be related to the contrast observed between termite resistance and fungal decay resistance.

Mechanical Properties: Hardness and Bending Properties

Figure 4 shows the Brinell hardness of the three Meliaceae species on the transverse, radial and tangential surfaces. On the transverse surface, the mean hardness values were 60.8 N/mm^2 (*S. macrophylla*), 52.4 N/mm^2 (*T. ciliata*), and 58.7 N/mm^2 (*A. indica*). Although the value for *T. ciliata* was lower than those of the other species, no significant differences were observed among the three species (Fig. 4). On the radial surface, *S. macrophylla* showed the highest mean hardness value (18.4 N/mm^2), which was statistically similar to that of *T. ciliata* (14.7 N/mm^2). *A. indica* showed the lowest value (14.1 N/mm^2), which was significantly lower than that of *S. macrophylla* ($p < 0.05$), though it did not significantly differ from *T. ciliata* (Fig. 4). On the tangential surface, *A. indica* showed a significantly lower hardness than the other two species at 1% level (15.4 N/mm^2). No significant difference was observed between *S. macrophylla* and *T. ciliata*: 25.8 N/mm^2 and 24.2 N/mm^2 (Fig. 4).

A. indica tended to show lower hardness, particularly on the radial and tangential surfaces, than the other two Meliaceae species. In general, wood hardness is closely related to wood density, and the hardness is often considered an indicator of resistance to mechanical damage and deterioration (Esteves *et al.* 2014). However, in the present study, the densities of *A. indica* in the termite and decay tests were not consistently lower than those of the other species (Tables 2 and 3), whereas its decay resistance was clearly inferior (Fig. 3). This suggests that the lower resistance of *A. indica* cannot be explained solely by density or hardness. The lower hardness of *A. indica* on the tangential surface apparently reflects some local surface-related weakness, but this alone is unlikely to account for the markedly greater mass loss observed in the fungal decay tests. Therefore, factors other than basic properties are likely to have contributed to the lower decay resistance of *A. indica*.

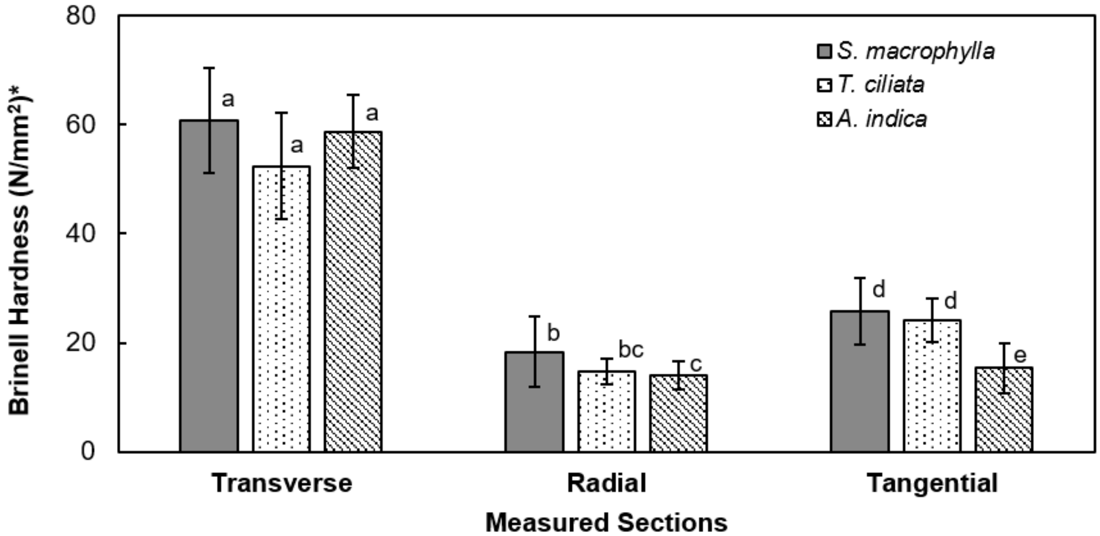

Fig. 4. Brinell hardness of the tested Meliaceae species (mean ± SD) (n = 3). Note: * Mean values with same letter are not significantly different among wood species within each group (transverse or radial or tangential) according to the Tukey-Kramer test ($p > 0.05$).

Figure 5 shows the bending properties of the tested Meliaceae species. The MOR was not significantly different among the species, though *S. macrophylla* showed the highest mean value (98.1 MPa), followed by *T. ciliata* (80.0 MPa) and *A. indica* (76.4 MPa) (Fig. 5a). Similarly, no significant differences were observed in the MOE, whereas *A. indica* showed the lowest mean value among the species: 9.5 GPa (*S. macrophylla*), 9.9 GPa (*T. ciliata*), and 7.9 GPa (*A. indica*) (Fig. 5b).

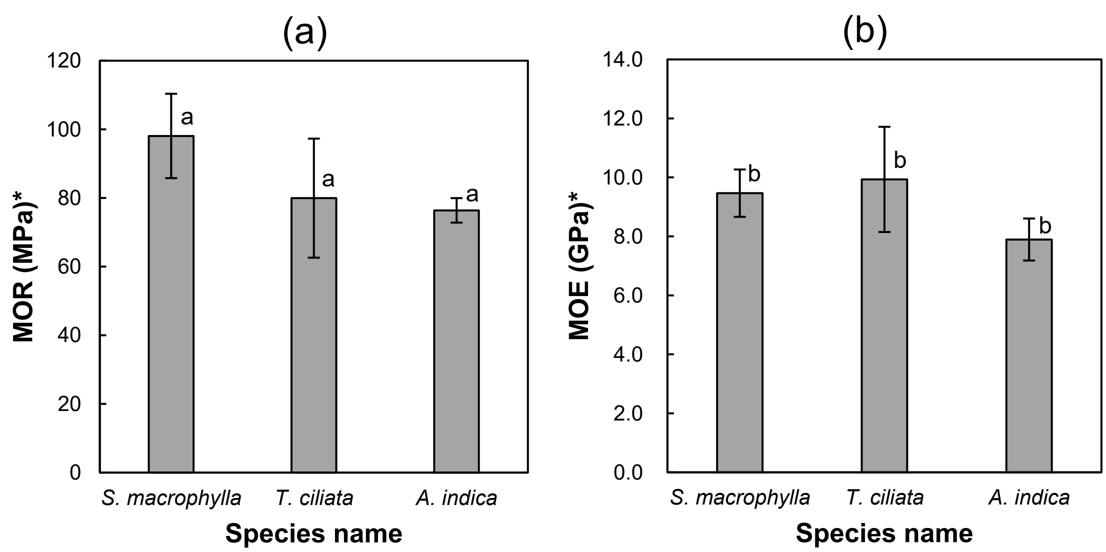

Fig. 5. Bending properties of the tested Meliaceae species (mean ± SD) (n = 5): (a) MOR and (b) MOE. Note: * Mean values with same letter are not significantly different according to the Tukey-Kramer test ($p > 0.05$).

Table 4 shows the air-dried densities of the specimens used in the bending test. The mean densities of *S. macrophylla* and *T. ciliata* were statistically similar, whereas that of *A. indica* was significantly lower than those of the other species. In general, bending properties depend on multiple factors, including species, growth conditions, and timber processing history. The wood density reflects the proportion of cell wall; therefore, both strength and stiffness are generally positively related to the wood density (Dinwoodie 2000; Hassan *et al.* 2019). The relatively low MOE of *A. indica* was therefore likely related to its lower density in the bending specimens. The similar tendency might also explain its relatively low MOR, although the difference was not statistically significant among the tested species. Since the density of *A. indica* in the bending test was lower than that measured in the termite and decay tests, the present bending results might partly reflect density variation among the sampled boards rather than a consistent species-level trend. Therefore, the lower bending properties of A. indica are likely to reflect, at least in part, variation in the sampled material.

Table 4. Air-dried Densities of Specimens used in the Bending Test (mean ± SD)

Species Name	Air-dried Density (g/cm^3)*
Swietenia macrophylla	0.56 ± 0.04^a
Toona ciliata	0.57 ± 0.01^a
Azadirachta indica	0.47 ± 0.02^b

* Mean values with same letter are not significantly different by Tukey-Kramer test ($p > 0.05$).

Among the tested species, *T. ciliata* may be regarded as the species most comparable to *S. macrophylla*, which is already widely used as a high-value timber. In the present study, *T. ciliata* showed hardness, MOR and MOE values broadly comparable to those of *S. macrophylla* (Fig. 4, Fig. 5). This suggests that *T. ciliata* might have potential for similar applications, though additional factors, such as dimensional stability, processability, appearance, and acoustic properties, would also need to be considered for practical use. Anatomically, *S. macrophylla* is generally described as a semi-ring porous wood (Husein *et al.* 2014), whereas *T. ciliata* ranges from semi-ring porous to ring porous wood depending on growth environment (Heinrich and Banks 2006). Such differences in vessel distribution may influence bending properties by affecting stress concentration and crack initiation around vessel-rich areas. In this context, the slightly lower MOR and MOE of *T. ciliata* compared with *S. macrophylla* may partly reflect anatomical differences in pore arrangement. Nevertheless, the overall similarity in mechanical properties suggests that *T. ciliata* remains a promising alternative timber species with properties broadly comparable to those of *S. macrophylla*.

Expectation of Timber Use

The results obtained in this study suggest that *S. macrophylla* and *T. ciliata* have potential as alternative timber resources for sustainable wood utilization, with possible implications for diversified timber production and land-use systems.

The present results indicate that the biological performance of *T. ciliata* is comparable to that of *S. macrophylla* and durable Tanzanian native species such as *P. angolensis* and *Afzelia quanzensis* (Nakai and Yoshimura 2020). Its mechanical properties were also similar to those of *S. macrophylla*. These findings suggest that *T. ciliata* could serve as a promising alternative timber species in Tanzania for both local use and commercial applications. In particular, its comparable biological performance and mechanical properties indicate that *T. ciliata* might have potential utilization similar to that of *S. macrophylla*, although further evaluation of processing properties, dimensional stability, and appearance would be required for high-value applications.

In contrast, *A. indica* showed lower biological performance than the other Meliaceae species, particularly against wood decay fungi. The trees of *A. indica* have been well known as an important medicinal and multipurpose tree in India, its bark, leaves, flowers, fruits and seeds are used for traditional medicine and other non-timber forest products (NTFPs) (Praciak *et al.* 2013). These NTFPs contribute to both local livelihoods and global markets. However, the present results suggest that the wood itself may require caution when considered for applications where high decay resistance is required. High biological performance of wood is important not only for exterior use but also for interior applications, including musical instruments, where long-term dimensional and material stability are often required. Although *A. indica* wood has previously been reported as durable (Hiware 2015), the results of this study did not support such a general evaluation, particularly with respect to fungal decay resistance. Therefore, efficient utilization of *A. indica* wood may still be possible, but further technical improvement, such as appropriate drying, preservation, or modified-use strategies, would be required.

Consequently, the results of this study indicate that *T. ciliata* has biological performance and mechanical properties comparable to those of *S. macrophylla*. Its biological performance is also comparable to some durable Tanzanian native timbers. In contrast, *A. indica* might be suitable for more limited applications unless additional treatments are applied to improve its resistance to fungal decay.

CONCLUSIONS

1. The tested Meliaceae species, *S. macrophylla*, *T. ciliata*, and *A. indica*, were generally resistant to termite attack, however the decay resistance was species dependent. In particular, *A. indica* showed low resistance to both white-rot and brown-rot fungi despite its comparable density. This suggests that the fungal susceptibility of *A. indica* is likely governed more by chemical durability, than by density or hardness.
2. *T. ciliata* showed mechanical properties comparable to those of *S. macrophylla*. The biological performance of *T. ciliata* was also similar to that of *S. macrophylla* and comparable to that of durable Tanzanian native species. These results indicate that *T. ciliata* has potential as an alternative timber resource for sustainable wood utilization in tropical regions.

ACKNOWLEDGMENTS

This work was supported by Japan International Forestry Promotion and Cooperation Center (JIFPRO) as a part of the applied project, "Wood Processing Technique for Fast Growing Tropical Timber", an empirical research and/or demonstration study project, Knowledge Project, funded by the Japan Forestry Agency. Additionally, this work was also supported as a part of joint study between the Yamaha Corporation and Kyoto University, which is based on the three parties' collaboration with the Yamaha

Corporation, the Research Institute for Sustainable Humanosphere at Kyoto University and the Graduate School of Agriculture at Kyoto University. The author gratefully thanks Yoshiyuki Kashima, Kazuki Soga, and Hisaaki Mukai, of the Yamaha Corporation, for their kind technical support to implement this study. Further appreciation surely goes to a technical staff of Kyoto University, Akio Adachi, and all members of the relevant companies and organizations.

REFERENCES CITED

Acanakwo, E. F, Sheil, D., and Moe, S. R. (2019). "Wood decomposition is more rapid on than off termite mounds in an African savanna," *Ecosphere* 10(1), e02554. https://doi.org/10.1002/ecs2.2554

Bhattacharyya, A., Yadav, R. R., Borgaonkar, H. P., and Pant, G. B. (1992). "Growth-ring analysis of Indian tropical trees: Dendroclimatic potential," *Current Science* 62(11), 736-742.

Cambers, J. Q., Higuchi, N., Schimel, J. P., Ferreira, L. V., and Melack, J. M. (2000). "Decomposition and carbon cycling of dead trees in tropical forests of the central Amazon," *Oecologia* 122(3), 380-388. https://doi.org/10.1007/s004420050044

da Mota Porto, A. C., and Novaes, E. (2025). "Prediction of current and future environmental suitability for *Toona ciliata* cultivation in Brazil," *Discover Forests* 1, 27. https://doi.org/10.1007/s44415-025-00029-w

Dinwoodie, J. M. (2000). "Deformation under load," in: *Timber: Its Nature and Behaviour*, Second Edition, J. M. Ginwoodie (ed.), CRC Press, Boca Raton, FL.

Doggart, N., Morgan-Brown, T., Lyimo, E., Mbilinyi, B., Meshack, C. K., Sallu, S. M. and Spracklen, D. V. (2020). "Agriculture is the main driver of deforestation in Tanzania," *Environmental Research Letters* 15, article 034028. https://doi.org/10.1088/1748-9326/ab6b35

Esteves, B., Nunes, L., Domingos, I., and Pereira, H. (2014). "Improvement of termite resistance, dimensional stability and mechanical properties of pine wood by paraffin impregnation," *European Journal of Wood and Wood Products* 72, 609-615. https://doi.org/10.1007/s00107-014-0823-7

Gupta, S. C., Prasad, S., Tyagi, A. K., Kunnumakkara, A. B., and Aggarwal, B. B. (2017). "Neem (*Azadirachta indica*): An Indian traditional panacea with modern molecular basis," *Phytomedicine* 34, 14-20. https://doi.org/10.1016/j.phymed.2017.07.001

Heinrich, I., and Banks, J. C. G. (2006). "Tree-ring anomalies in *Toona ciliata*," *IAWA Journal* 27(2), 213-231.

Hiware, S. (2015). "Neem (*Azadirachta indica*)," in: *Sustainable Horiculture in Semiarid Dry Lands*, Springer India, New Delhi. https://doi.org/10.1007/978-81-322-2244-6

Husein, I., Sadiyo, S., Nugroho, N., Wahyudi, I., Agustina, A., Komariah, N., Khabibi, J., Ali, C. Y. C. P. D., Kahar, T. P., Wijayanto, A., and Jamilah, M. (2014). "Electrical properties of Indonesian hardwood case study: *Acacia mangium*, *Swietenia macrophylla* and *Maesopsis eminii*," *Wood Research* 59(4), 695-704.

Itani, J. (2023). "Chapter 6," in: *Tsukuru/Tsukau, Ecological Anthropology Challenging Session 4*, J. Itani (ed.), Kyoto University Press, Kyoto, Japan. (in Japanese)

JIS K 1571 (2010). "Wood preservatives – Performance requirements and their test methods for determining effectiveness," Japanese Industrial Standards Committee, Tokyo, Japan.

JIS Z 2101 (2009). "Methods of test for woods", Japanese Industrial Standards Committee, Tokyo, Japan.

Kraus, W. (1995). "Biologically active ingredients," in: *The Neem Tree: Sources of Unique Natural Products for Integrated Pest Management, Medicine, Industry and Other Purposes*, H. Schumutterer (ed.), Weinheim, NY.

Krisnawati, H., Kallio, M., and Kanninen, M. (2011). *Swietenia macrophylla King: Ecology, Silviculture and Productivity*, CIFOR, Bogor, Indonesia.

Kurimoto, S., Takaishi, Y., Ahmed, F. A., and Kashiwada, Y. (2014). "Triterpenoids from the fruits of *Azadirachta indica* (Meliaceae)," *Fitoterapia* 92, 200-205. https://doi.org/10.1016/j.fitote.2013.11.004

Machado, G. O., Cookson, L. J., Christoforo, A. L., Polito, W. L., da Silva, M. R., Junior, C. C., and Lahr, F. A. R. (2013). "Wood preservation based on Neem oil: Evaluation of fungicidal and termiticidal effectiveness," *Forest Products Journal* 63(5/6), 202-206. https://doi.org/10.13073/FPJ-D-13-00050

Mao, W., Song, H., Li, Y., Wang, Y., Lin, H., Yao, C., Zhou, W., Yang, B., Chen, X., and Li, P. (2021). "Efficient plant regeneration and genetic transformation system of the precious fast-growing tree *Toona ciliata*," *Industrial Crops & Products* 172, article 114015. https://doi.org/10.1016/j.indcrop.2021.114015

Nakai, K. (2025). "Participatory forest management in the Miombo woodlands of Tanzania: Developments and challenges," *Sustainable Humanosphere* 21, 27-33. (in Japanese) https://doi.org/10.69212/humanosphere.21.0_27

Nakai, K., and Yoshimura, T. (2020). "African Blackwood (*Dalbergia melanoxylon*) and other local Tanzanian tree species' biological performance against subterranean termites and wood decay fungi," *BioResources* 15(2), 2994-3005. https://doi.org/10.15376/biores.15.2.2994-3005

Ohmura, W., Doi, S., Aoyama, M., and Ohara, S. (2000). "Antifeedant activity of flavonoids and related compounds against the subterranean termite *Coptotermes formosanus* Shiraki," *Journal of Wood Science* 46(2), 149-153. https://doi.org/10.1007/BF00777362

Okanlawon, F. B., Adegoke, O. A., Olantuji, O. A., Okon-Akan, O. A., and Akala, L. O. (2020). "Effectiveness of *Azadirachta indica* A. Juss (Neem) seed oil in controlling wood termite," *J. Appl. Science and Environmental Management* 24(9), 1541-1544. https://doi.org/10.4314/jasem.v24i9.9

Praciak, A., Pasiecznik, N., Sheil, D., van Heist, M., Sassen, M., Correira, C. S., Dixon, C., Fyson, G. E., Rushforth, K., and Teeling, C. (2013). "*Azadirachta indica*, *Swietenia macrophylla*," in: *The CABI Encyclopedia of Forest Trees*, Bonham V. (Ed.), CABI international, OX, UK.

Tascioglu, C., Yalcin, M., Sen, S., and Akcay, C. (2013). "Antifungal properties of some plant extracts used as wood preservatives," *International Biodeterioration & Biodegradation* 85, 23-28. https://doi.org/10.1016/j.ibiod.2013.06.004

United Nations Environment Programme (UNEP) (2015). *The Ecological and Economic Benefits of Forests in Tanzania: A Case for Investing in Natural Forest Management*, Forestry and Beekeeping Division of the Ministry of Natural Resources and Tourism of Tanzania and the Tanzania Forest Conservation Group, Nairobi, Kenya.

Article submitted: April 15, 2026; Peer review completed: May 9, 2026; Revised version received: May 13, 2026; Accepted: May 28, 2026; Published: June 15, 2026.
DOI: 10.15376/biores.21.3.6960-6974