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Annals of Forest Science (2018) 75: 39
https://doi.org/10.1007/s13595-018-0716-8

ORIGINAL PAPER

Comparison of teak wood properties according to forest management: short versus long rotation

Dwi Erikan Rizanti[1,2] · Wayan Darmawan[2] · Béatrice George[1] · André Merlin[1] · Stéphane Dumarcay[1] · Hubert Chapuis[1] · Christine Gérardin[1] · Eric Gelhaye[3] · Phila Raharivelomanana[4] · Rita Kartika Sari[2] · Wasrin Syafii[2] · Rozi Mohamed[5] · Philippe Gerardin[1]

Received: 12 October 2017 / Accepted: 21 February 2018 / Published online: 16 March 2018

Abstract

• ***Key message*** **Teak (*Tectona grandis* L.f.) is one of the most important tropical hardwood tree species, which is widely planted in Indonesia. Wood properties are strongly influenced by forest management conditioning further utilization of wood.**

• ***Context*** In Indonesia, teak wood has been supplied from the state forests (Perhutani) for long rotation teak and from community teak plantations for short rotation teak. Short rotation teak has been harvested at 7–10 years and long rotation teak at 40–60 years.

• ***Aims*** This paper discusses the characterization of technical properties of short and long rotation teak wood based on the chemical, anatomical, physical, and mechanical properties.

• ***Methods*** The properties of short rotation and long rotation teak woods were characterized by measuring their density, extractive contents, chemical composition, swelling, wettability, water sorption isotherm, decay resistance, anatomical properties, bending strength (modulus of rupture (MOR), modulus of elasticity (MOE)), and hardness.

• ***Results*** The results indicate that short rotation teak was not particularly different in swelling, MOE and MOR, and Brinell hardness compared to long rotation teak, although it was less dense and less durable due to lower heartwood and extractive contents. Therefore, careful attention should be given to the use of short rotation teak in some wood-processing technologies.

• ***Conclusion*** Lower wood density and durability of the short rotation compared to the long rotation teak will restrict its utilization to some extent for both indoor and outdoor applications. Fast-growing teak from community cannot be used as usual heartwood teak from Perhutani because of the very low proportion of useful heartwood in the stem.

Handling Editor: Barry Alan Gardiner

Contribution of the co-authors Dwi Erikan Rizanti: carrying out the experiments, interpreting the results, and writing the first draft of the paper.
Béatrice George, Stéphane Dumarcay, Hubert Chapuis, André Merlin, Christine Gerardin, Eric Gelhaye: supervising experimental work and interpreting the results.
Phila Raharivelomanana, Wasrin SYAFII, Rozi Mohamed, Rita Kartika Sari: correction of the paper as participant of Bio-Asie program.
Philippe Gerardin, Wayan Darmawan: co-designing and coordination of the master thesis of Dwi Erikan Rizanti, supervision of work, interpreting the results, and final correction of the paper.

✉ Philippe Gerardin
philippe.gerardin@univ-lorraine.fr

[1] Université de Lorraine , Inra, LERMAB F-54000, Nancy, France

[2] Department of Forest Products, Bogor Agricultural University, Kampus IPB Dramaga, Bogor, Indonesia

[3] Université de Lorraine, Inra, IAM, F-54000, Nancy, France

[4] Ecosystèmes Insulaires Océaniens UMR 241, Université de la Polynésie Française, BP 65670 FAAA, Faaa, 98702 Tahiti, Polynésie Française, France

[5] Department of Forest Management, Faculty of Forestry, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

Keywords Extractives · Durability · Forest management · Rotation · *Tectona grandis* · Wood properties

1 Introduction

Teak (*Tectona grandis* L.f.) is one of the most important tropical hardwood tree species in Indonesia and the most highly valued hardwoods. It is planted widely in Java by Perhutani, a state forest enterprise in Indonesia, which is responsible for the management of teak. The teak planted by Perhutani has been felled at the age of 40 to 60 years (long rotation teak) and processed for shipbuilding, outdoor equipment, and furniture in large quantities. Due to increasing demand, much of the teak wood supply has been from community teak plantations which are planted and managed by communities and private companies not only in Java but also in other parts of Indonesia.

Short rotation teak trees grow fast in the regions where they are planted and are harvested at a younger age of 7 to 10 years (short rotation teak) leading therefore to wood with a high proportion of juvenile wood and sapwood. In comparison with mature wood, juvenile wood possesses smaller and thin-walled shorter fibers with larger microfibril angles, lower density, and lower strength properties (Evans et al. 2000; Koubaa et al. 2005; Clark et al. 2006; Adamopoulos et al. 2007; Gryc et al. 2011). Moreover, the characteristics of juvenile wood are well-known to contribute to undesirable solid wood properties (Zobel 1984). It may cause serious problems for particular products, especially veneer or solid wood products. This is due to its low bending strength and dimensional instability. Darmawan et al. (2015) also reported that long rotation teak has higher heartwood content than short rotation teak. The heartwood portion of short rotation teak at 10 years is about 40%, whereas the proportion of long rotation teak at an age of 40 years is about 80%. This causes lower resistance of short rotation teak wood that restricts its utilization, although it might still be superior to many other less resistant timbers from fast-growing plantations like Sengon (*Paraserianthes* (*L.*) *Nielsen* (*Jeungjing*)) or Jabon (*Neolamarckia cadamba* (*Roxb.*) *Bosser*).

Although Darmawan et al. (2015) conducted research on short rotation and long rotation teak wood to characterize their radial profiles and average trends in density, shrinkage, fiber length, microfibril angle (MFA), and bending strength (modulus of rupture (MOR) and modulus of elasticity (MOE)) as a function of position relative to the pith and bark, however, little is known on their chemical composition, extractive content, wettability, color changes, and durability.

The present study was designed to investigate some of these less investigated short rotation and long rotation teak woods properties, namely, the chemical composition (holocellulose, cellulose, lignin, and extractive contents), dimensional stability (swelling and water sorption), wettability (contact angle), color changes, decay resistance, bending strength (MOR and MOE), Brinell hardness, and anatomical properties (vessel area and vessel frequency). The focus of this study is to investigate the comparison of wood properties between short rotation and long rotation teak wood and the effects of wood chemical composition on its technological properties with respect to its utilization.

2 Materials and methods

2.1 Sampled trees and wood sample preparation

Sample trees were obtained from plantation forests managed by the state-owned enterprise, Perhutani, and a local community in Java, Indonesia. The plantation sites were located at Madiun (7° 37′ 4.901″ S/111° 31′ 28.099″ E, 95 m asl), East Java for the Perhutani teak and at Bogor (6° 35′ 23″ S/106° 47′ 29″ E, 127 m asl) West Java for the community teak. Differences in growing conditions (environment, genetics, and silviculture) between West Java and East Java resulted in variations in the teak growth. Bogor, West Java, has a high annual rainfall (average 3500 mm/year), and dry conditions for 2–3 months with an average temperature of 27 °C. Madiun, East Java, has an average rainfall below 2000 mm/year and dry conditions for 4–6 months with an average temperature of 29 °C. Fast-growing clonal seeds have been selected and planted at nutrient-rich sites in the community forest at Bogor, whereas Perhutani has utilized seeds from its production areas, probably from semi-wild provenances.

Three trees each of long rotation and short rotation teak were selected from each plantation site as representative specimens. Defect-free, straight sample trees were selected to minimize tree-to-tree variation. The long rotation trees were 40 years old and 30 cm in average diameter at breast height (1.3 m above ground level). The short rotation trees were 10 years old, 6–10 m in height of branch-free straight bole, and 24 cm in average diameter at breast height level. From the felled tree, a 2-m length basal log was removed and wrapped in plastic, kept cold, and maintained in the green condition before being transported to the wood workshop for preparation of test specimens.

The sample logs were bandsawed in a live sawing pattern to produce pieces with a thickness of 20 mm. The pieces were resawn again to produce timber in sizes of 20 × 100 × 200 mm (radial, tangential, longitudinal). Specimens from the Perhutani teak contained only brown yellowish heartwood, while specimens from the community teak contained light-

colored sapwood. The specimens were air-dried to (12–15% m.c. and used for further preparation of smaller samples for studying different wood properties) (Fig. 1).

Samples of 10 × 20 × 30 mm were prepared for the swelling tests, samples of 20 × 20 × 20 mm for density, samples of 5 × 20 × 200 mm for mechanical tests (MOE, MOR), samples of 20 × 20 × 200 mm for the Brinell hardness test, samples of 5 × 20 × 200 mm for wettability test, and samples of 5 × 20 × 30 mm for durability tests.

2.2 Determination of extractive content

Short rotation and long rotation teak wood samples were ground to fine sawdust before drying at 103 °C. Sequential extraction of each wood powder sample, approximately 10 g, was carried out in a Soxhlet apparatus using in sequence four solvents of increasing polarity: dichloromethane, acetone, toluene/ethanol (2/1, (*v*/*v*)), and water. After extraction, organic solvents were evaporated under vacuum using a rotary evaporator, while water was freeze-dried. Crude extracts were stored in desiccators under vacuum for final drying and weighed to determine extractive content based on moisture-free wood powder. Dried extractives were stored in a freezer before GC–MS analyses.

2.3 GC–MS analysis

A Clarus 680 GC gas chromatogram coupled with a SQ8 Mass Spectrometer (Perkin Elmer, Waltham, MA, USA) was used for this analysis. Gas chromatography was carried out using a capillary column (J&W Scientific, Folsom, CA, USA, DB-5, 30 m × 0.25 mm × 0.25 μm). Two milligrams of dry extract was dissolved in 50–100 μL of *N*,*O*-*bis*(trimethylsilyl) trifluoroacetamide containing 1% trimethylchlorosilane (BSTFA/1% TMCS). The solution was vortex stirred and heated at 70 °C for 6 h. After evaporation of the solvent, the residue was diluted in 1 mL of ethyl acetate. The injection (1 μL) was performed at 250 °C in the splitless mode. Helium was used as carrier gas at constant flow (1 mL/min). Chromatographic conditions were as follows: initial temperature 80 °C, 2 min isothermal, 10 °C min^{-1} to 190 °C, 15 °C min^{-1} to 280 °C, 5 min isothermal, 10 °C min^{-1} to 300 °C, and 14 min isothermal. Ionization was achieved by electron impact at 70 eV ionization energy. Most of the components were identified by comparing the mass spectra with the NIST Library database (2011) with match and reverse match factors above 0.750.

2.4 Chemical composition

2.4.1 Holocellulose

The method was performed according to Rowell (2005). 2.5 g of wood sawdust was placed in a 250-mL Erlenmeyer flask and 80 mL of hot distilled water added, followed by 0.5 mL acetic acid, and 1 g of sodium chlorite. An optional 25-mL Erlenmeyer flask was inverted in the neck of the reaction flask to condense vapor. The mixture was heated in a water bath at 70 °C. After 1 h, 0.5 mL of acetic acid and 1 g of sodium chlorite were added. Addition of 0.5 mL acetic acid and 1 g of sodium chlorite was repeated every hour until the residual solid material was turned white indicating the removal of most of the lignin fraction. It usually takes 6 to 8 h of reaction. Holocellulose was filtered on filter paper using a Büchner funnel until the filtrate became colorless, washed with acetone, dried at 103 °C for 24 h, and weighed.

2.4.2 Cellulose

The cellulose was obtained by the Kurschner and Hoffner method using nitric acid in ethanol (HNO_3 (16 N), ethanol (95%)) (Antunes et al. 2000). One gram of extracts free sawdust was placed in a 250-mL flask. Forty milliliters of ethanol and 10 mL of nitric acid were added and the mixture was placed under reflux at 100 °C. After 1 h, the alcoholic nitric acid solution was discarded and a fresh volume of 40 mL of ethanol and 10 mL of nitric acid was added. This operation

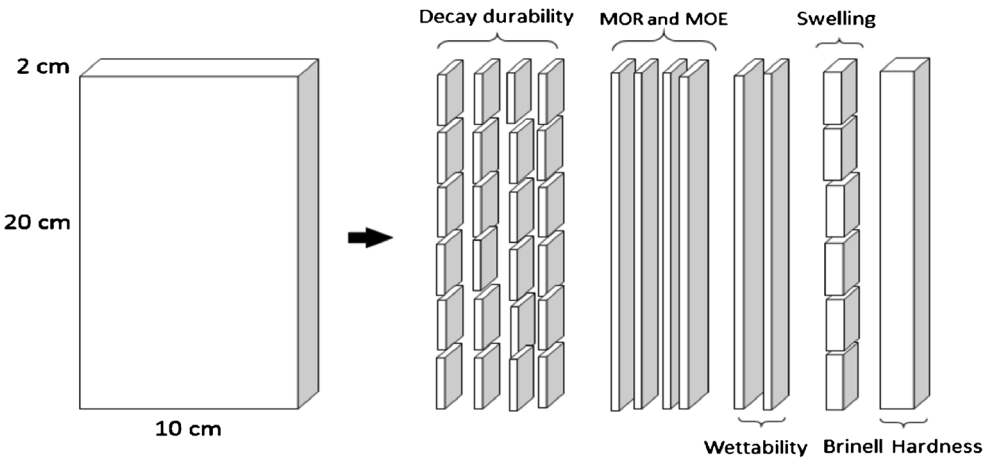


Fig. 1 The cutting method of wood specimens for tests

was repeated one additional time. After the third hour of hydrolysis, the cellulose was washed with ethanol, filtered, dried in an oven at 103 °C for 24 h, and weighed.

2.4.3 Hemicellulose

Hemicellulose content was obtained from the difference between holocellulose content and cellulose content. The hemicellulose content was calculated using the following formula:

$$\text{Hemicellulose content } (\%) = \text{Holocellulose } (\%) - \text{Cellulose } (\%)$$

2.4.4 Lignin

The lignin fraction was obtained by the method of Nguila Inari et al. (2007), which consists in removing polysaccharides. 0.175 g of dried extract free sawdust was placed in a 50-mL centrifuge tube. 1.5 mL of concentrated sulfuric acid (≥ 97.5%) was added to the sawdust. The tubes were closed and placed in a water bath equipped with a stirring system at 30 °C for 1 h. After this period, the mixture was diluted with 42 mL of distilled water to obtain a sulfuric acid concentration of 30%. The tubes were closed and autoclaved for 1 h and 30 min at 120 °C. After autoclaving, the mixture was diluted with 100 mL of distilled water and filtered on a Büchner funnel. The black residue of lignin was dried at 103 °C for 48 h until constant mass. Lignin content is determined by the following formula:

$$\text{Lignin content } (\%) = (\text{Mass of lignin}/0.175) \times 100$$

2.5 Density

Density was calculated as the air-dried mass (moisture content 12–15%) divided by the air-dried volume of the sample. Sample dimensions were measured along the radial, tangential, and longitudinal directions using a 0.01-mm precision caliper in air-dried condition.

2.6 Swelling test

The method was performed according to Edou Engonga et al. (1999, 2000). Six replicates of short rotation and long rotation teak woods dried for 48 h at 103 °C, cut into samples of 10 × 20 × 30 mm, were measured according to their radial, longitudinal, and tangential directions to obtain the dry volume. Test blocks were soaked in water in a beaker. The beaker was placed in a desiccator and subjected to a vacuum (30 mbar) for 1 h. The samples were left submerged in water for 1 day. After this period, the water contained in the beaker was changed and cycle of soaking repeated four times with change of water between each cycle. Samples were then removed from the water and their dimensions measured to obtain the wet volume. Volumetric swelling of wood was calculated with the following formula:

$$S = [(V_W - V_D)/V_D] \times 100$$

where S is swelling of wood, V_W is wet volume of wood, and V_D is the initial dry volume of wood.

2.7 Microscopic wood anatomy measurements

Thin transverse sections (12 μm in thickness) were prepared on a sliding microtome. The sections were double stained with Safranin (1%) and Astra (1%). Digital images of transverse sections were captured with a digital camera mounted on photonic microscope and analyzed with the ImageJ 1.47s software to determine the vessel area and vessel frequency (vessel number per unit area). Wood porosity was estimated using the ImageJ 1.47s software as the ratio of vessel area on total area of the sample.

2.8 Mechanical tests

Modulus of elasticity (MOE) and modulus of rupture (MOR) were determined with samples of 5 × 20 × 200 mm according to EN 310 using a three point bending device INSTRON 4467 universal testing machine (Buckinghamshire, UK) (European Standard 1993).

2.9 The Brinell hardness test

This test was conducted according to EN 1534 on the test samples with a dimension of 20 × 20 × 200 mm (European Standard 2010). The test is performed on each of the tangential and radial faces of the specimens. The ball diameter is 10 mm; a force is applied gradually until its value reaches 1960 Newtons in 20 s, and this force is maintained normally 30 s, then slowly discharged. The measure of the depression gives the Brinell hardness. The Brinell hardness was then obtained using the following formula:

$$\text{HB} = 2F/\left\{g \times \pi \times D \times \left[D - \left(D^2 - d^2\right)^{1/2}\right]\right\}$$

where HB is the Brinell hardness (N/mm^2), F is the nominal force (N), g is the acceleration of gravity (9.8 m/s^2), D is the ball diameter, and d is the diameter of the residual impression (mm).

2.10 Contact angle measurements

The contact angle of teak wood was measured by the optical method using a Krüss model DSA10 (Hamburg, Germany) at

room temperature and humidity with water and glycerol as test liquids. Ten drops of liquid were used for each wood sample. For each drop, 11 contact angle measurements were performed automatically (one measurement each 2 s).

2.11 Water sorption isotherm

Isotherms were performed using a dynamic gravimetric water sorption analyzer from Surface Measurement Systems (DVS-Intrinsic) (Allentown, USA) on small teak chips previously extracted (first extraction with acetone followed by toluene/ethanol (2/1, (*v*/*v*)) or not samples (Simo-Tagne et al. 2016). An initial mass of approximately 10 mg of each sample was used for each measurement. The sorption cycles applied started from 0% RH at 20 °C. Samples were maintained at a constant RH level until the weight change per minute (dm/dt) value reached 0.0005% per min.

2.12 Decay resistance (European Standard 1996)

Decay resistance was evaluated according to a procedure modified from EN 113 (1986) described by Bravery (1979). In brief, white rot fungi *Coriolus versicolor* (L) *Quelet* (Strain CTB 863A) (*Cv*) and *Pycnoporus sanguineus* MUCL 51321 (*Ps*) were inoculated on sterile culture medium prepared from malt (40 g) and agar (20 g) in distilled water (1 L) in 9-cm Petri dishes and cultivated in an incubator at 22 °C temperature and 70% relative humidity for 7 days. After colonization of all the surface of Petri dishes by the mycelium, three short rotation or long rotation teak samples or European beech samples (*Fagus sylvatica* L.) used as control were put in each Petri dish and then incubated for another 12 weeks. Dimensions of the samples in this test were 5 × 20 × 30 mm with 12 replicates for each fungus tested. The weight loss (WL) due to degradation by fungus was calculated with the following equation:

$$\mathrm{WL} = [(M_0 - M_1)/M_0] \times 100$$

where WL is the weight loss ratio (%) and M_0 and M_1 are dry mass of the samples before and after exposure to fungus, respectively.

2.13 Color measurements (UV irradiation)

Samples were exposed in a QUV accelerated weathering tester from Q-Lab (Canterbury, USA) for 60 h. Cycle 1 of ASTM G154-2012 Standard test method "Standard Practice for Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Non-metallic Materials" was used. An UV-A 340 lamp was used for the irradiation at 0.89 W/m^2/nm to simulate the UV portion of the solar spectrum.

Color measurements using a reflectance spectrophotometer: (X-Rite spectrophotometer). The CIEL*a*b* color scale was used. The overall color differences (ΔE) were calculated using the following equation:

$$\Delta E_{\mathrm{ab}}{}^{*} = \left[\left(\Delta L^{*}\right)^2 + \left(\Delta a^{*}\right)^2 + \left(\Delta b^{*}\right)^2\right]^{1/2}$$

where ΔL*, Δa*, and Δb* are the difference of initial and final values. The L* value represents the lightness and varies from 100 (pure white) to zero (pure black). a* and b* are the chromaticity coordinates: + a* is for red, − a* for green, + b* for yellow, and − b* for blue. Zero is gray. A low ΔE* value corresponds to a low color difference.

Data availability All data generated or analyzed during this study are included in this published article.

3 Results

Results concerning extractives as well as holocellulose, cellulose, hemicellulose, and lignin are presented in Table 1.

Cumulate extractive content of long rotation teak wood was higher than extractive contents of short rotation teak wood. The long rotation teak which was 30 years older than the short rotation teak contained more extractives with higher structural diversity. Long rotation teak contained the highest fraction of low polarity compounds extracted with dichloromethane; meanwhile, short rotation teak contained the highest fraction of high polarity compounds extracted with water. Long rotation teak (less sapwood and more heartwood contents) contained slightly more holocellulose, cellulose, and hemicellulose contents compared to short rotation teak (more sapwood and lower heartwood content), but its lignin content was lower.

The chemical composition of short and long rotation teak extractives is presented in Table 2.

Due to the very low number and poor concentration of molecules detectable in chromatograms of the acetone and toluene/ethanol extractives of the short rotation teak, only compositions of methylene chloride extractives are indicated.

The dichloromethane, acetone, and toluene/ethanol extracts of long rotation teak contained tectoquinone as the main substance. The highest percentage of tectoquinone was in the acetone extract of long rotation teak representing 14.5% of the TIC (total ion current). The amount of tectoquinone was very small in the extracts of short rotation teak. It was only found in the acetone extract in the percentage of 1.5% of TIC.

Physical, anatomical, and mechanical properties of short rotation and long rotation teak woods are presented in Table 3.

The results indicate that long rotation teak had a greater density than short rotation teak. Except for one replicate, long rotation teak had higher dimensional stability compared to short rotation teak. The average swelling coefficient of long

Table 1 Extractive, holocellulose, cellulose, hemicellulose, and lignin contents of short rotation and long rotation teak woods

	Long rotation teak	Short rotation teak
Dichloromethane extractive content (%)	2.8 ± 0.10	0.5 ± 0.06
Acetone extractive content (%)	1.1 ± 0.28	0.3 ± 0.05
Toluene/ethanol (2/1) extractive content (%)	1.6 ± 0.15	0.4 ± 0.06
Water extractive content (%)	2.5 ± 0.45	2.5 ± 0.48
Total extractive content (%)	8.0 ± 1.55	3.7 ± 0.85
Holocellulose (%)	68.53 ± 0.63	67.50 ± 1.53
Cellulose (%)	49.18 ± 0.60	48.80 ± 1.19
Hemicellulose (%)	19.35 ± 0.92	18.70 ± 1.72
Lignin (%)	32.19 ± 0.76	35.53 ± 0.78

rotation teak is lower than that of short rotation teak. Vessel frequency is higher for short rotation teak compared to long rotation teak. The MOE and MOR values of short rotation teak wood were lower than those of the long rotation teak wood. Brinell hardness values are the average on radial and tangential penetrations. Long rotation teak wood had a greater Brinell hardness mean value than short rotation teak wood (Fig. 2).

Contact angles for short rotation and long rotation teak wood are presented in Fig. 3.

Figure 3a shows that contact angle for water drops was greater for long rotation teak with and without extractives compared to short rotation teak. There was a difference for the initial and final contact angles measured for long and short rotation teak. Due to the high water permeability of short rotation teak, the contact angle on its surface decreased rapidly with time. The contact angle of water on the surface of long rotation teak was larger from beginning up to end of the experiment compared to the contact angle of the short rotation teak.

Figure 3b shows the same tendency of contact angle when glycerol was used as test liquid. Long rotation teak with extractives had the higher contact angle value, followed by short rotation teak with extractives, long rotation teak without extractives, and short rotation teak without extractives. However, there was almost no change of contact angles from initial to final contact on the surface of long and short rotation teak. The small changes in contact angle of the glycerol on the surface of teak woods compared to water indicate that the penetration of glycerol was very slow, indicating that wettability was larger in short than in long rotation teak wood. The effect of wood species on the spreading and penetration of a

Table 2 Major compounds identified by GC–MS in the extractives of short rotation and long rotation teak woods

	Retention time	Name of products	Match	TIC (%)
Perhutani teak				
Dichloromethane	16.59	4α-Methyl-1-methylene-1,2,3,4,4α,9,10, 10α-octahydrophenanthrene	669	4.9
	17.35	Tectoquinone	893	6.4
	21.65	Squalene	909	65.5
	26.73	Campesterol TMS	843	3.6
	27.01	Stigmasterol TMS	852	4.6
	27.78	β-Sitosterol TMS	794	10.6
Acetone	16.43	Hemitectol TMS	ni	9.6
	16.56 and 16.67	Two phenanthrene derivatives	650	20.2
	17.38	Tectoquinone	874	58.1
	17.82	Tertbutylanthraquinone	642	7.1
	18.33	Methyltestosterone	625	5.1
Toluene: ethanol	11.88	1,2-Tetradecanediol	658	29.7
	16.83	4′-ethyl-biphenylcarboxylic acid	769	5.2
	17.51	Tectoquinone	651	10.3
	29.27	Tectol TMS	ni	10.7
	31.58	Unidentified sterol derivative	ni	19.9
	31.90	Unidentified sterol derivative	ni	24.3
Community teak				
Dichloromethane	16.59	Palmitic acid TMS	893	9.4
	17.69	Linoleic acid TMS	859	2.7
	26.85	Campesterol TMS	836	14.2
	27.15	Stigmasterol TMS	873	20.3
	27.96	β-Sitosterol TMS	800	53.3

(ni) for non identified

Table 3 Physical, anatomical, and mechanical properties of short rotation and long rotation teak woods (basic density, volumetric swelling, vessel frequency, MOE, MOR, and Brinell hardness)

	Long rotation teak	Short rotation teak
Basic density (kg/m^3)	664 ± 3	472 ± 2.65
Volumetric swelling (%)	7.2 ± 0.7	8.4 ± 0.5
Vessel frequency (vessels/mm^2)	4.2	5.5
MOE (N/mm^2)	12,861.8 ± 40.9	9929.3 ± 687.0
MOR (N/mm^2)	118.9 ± 1.9	97.4 ± 12.6
Brinell hardness (N/mm^2)	35.2 ± 0.6	27.9 ± 0.3

liquid strongly depend on the texture and structure of the wood surface. The short rotation and long rotation teak woods displayed differences in texture and structure (Fig. 2) leading to different vessel frequencies (Table 3).

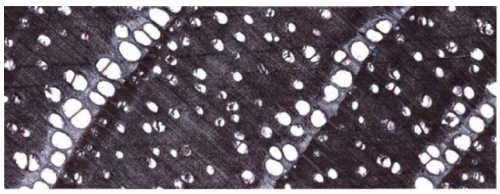
The full sorption–desorption isotherm is presented in Fig. 4.

The resistance of the teak wood samples to the white rot decay fungi *Coriolus versicolor* and *Pycnoporus sanguineus* is presented in Fig. 5.

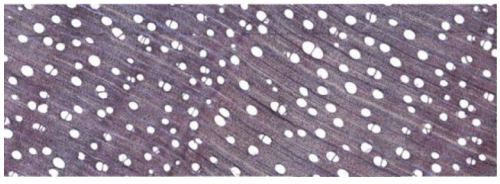
Wood durability tests performed with white rot fungi indicate strong differences between long rotation and short rotation teak. The weight losses of long rotation teak wood samples exposed to *Coriolus versicolor* or *Pycnoporus sanguineus* were in both cases very low, while weight losses of short rotation teak wood samples were always higher. Mass losses of beech wood samples exposed to *Coriolus versicolor* or *Pycnoporus sanguineus* present the highest weight losses confirming the virulence of both fungal strains investigated.

Figure 6 presents the variation of ΔL^*, Δa^*, Δb^*, and ΔE^* with irradiation time.

The color of long and short rotation teak wood tends to gradually change after UV irradiation. Both long and short rotation teak wood tend to lightened and yellowed after 60 h of UV irradiation.



Long rotation teak



Short rotation teak

Fig. 2 Transverse sections of teak wood according to forest management

4 Discussion

4.1 Extractive content

Previous studies carried out in our laboratory indicated extractive content of 12.65% for heartwood of long rotation teak aged of 64 years (Wijayanto 2014). The same amount of extractive content (12.7%) was reported by Miranda et al. (2011) for teak wood (50–70 years) from East Timor. Differences in extractive contents due to rotation age were also reported by Lukmandaru and Takahashi (2008). Other factors such as growth location, the type of solvent, and extraction techniques were also reported to influence extractive content (Moya et al. 2014). In addition, Wijayanto (2014) and Miranda et al. (2011) reported that heartwood contained also more dichloromethane-soluble extractive content (9.06 and 5.7%). The high nonpolar fraction in heartwood indicates that biomolecules responsible of teak durability are accumulated during the maturation process of teak wood (Miranda et al. 2011; Niamké et al. 2011; Lukmandaru and Takahashi 2008).

4.2 Chemical composition

Darmawan et al. (2015) reported that long rotation teak has less juvenile wood and has higher heartwood content compared to short rotation teak. Miranda et al. (2011) reported holocellulose and cellulose contents in heartwood of 50–70 years old teak wood from East Timor of 57.5 and 44.6%, respectively, higher than the contents present in sapwood (holocellulose 56.2% and cellulose 43.7%), while their lignin contents was more or less similar (32.2% in heartwood and 32.4% in sapwood).

4.3 Chemical composition of short and long rotation teak wood extractives

Squalene was the main compound identified in dichloromethane extracts. Wijayanto (2014) reported the same result for teak wood extracted with dichloromethane. Windeisen et al. (2003) also reported a similar result with petroleum solvent.

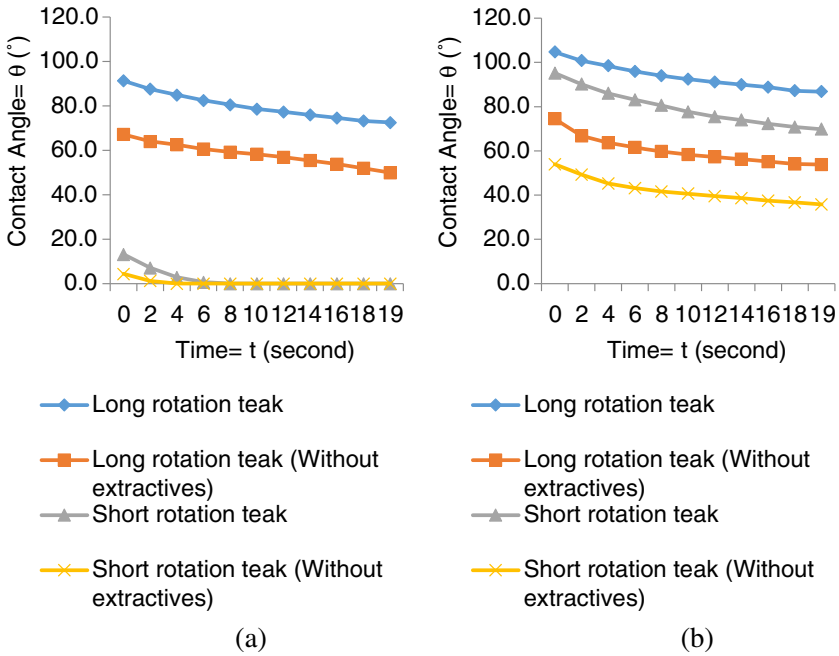


Fig. 3 Contact angle of short rotation and long rotation teak woods using water (**a**) and glycerol (**b**) as liquid

Lukmandaru and Takahashi (2009) showed that squalene was the main substance in ethanol-benzene extract.

The highest percentage of tectoquinone was identified in the acetone extract of long rotation teak. It is well-known that teak wood extractives contain mainly anthraquinones like tectoquinone, 1-hydroxy-2-methylanthraquinone, or pachybasin (Sumthong et al. 2006). Wijayanto (2014) also reported tectoquinone as the major component present in acetone extract of long rotation teak.

The amount of tectoquinone was very small in the extracts of short rotation teak. Considering that tectoquinone is responsible of teak natural durability (Lukmandaru and Ogiyama 2005), this difference in tectoquinone content may explain the lower decay durability of short rotation teak compared to long rotation one.

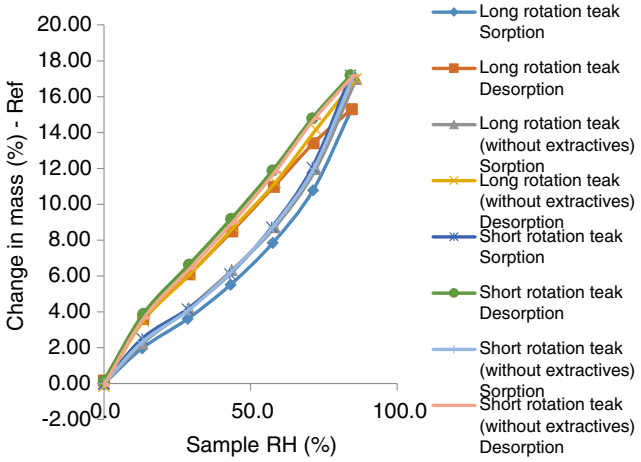


Fig. 4 Sorption and desorption isotherm of short rotation and long rotation

4.4 Density

The results indicate that long rotation teak had a greater basic density than short rotation teak. The value measured for long rotation teak was 664 kg/m^3, while this for short rotation teak was 472 kg/m^3. Martawijaya et al. (2005) found the density of long rotation teak to range from 620 to 750 kg/m^3 with an average of 670 kg/m^3. Darmawan et al. (2015) also reported the density of short rotation and long rotation teak woods to range from 443 to 535 and 635 to 714 kg/m^3 with average values of 486 and 670 kg/m^3, respectively. Results in this work indicate that the density of short and long rotation teaks conforms to the reported range.

4.5 Swelling

The results indicate that the long rotation teak with higher basic density presents lower volumetric swelling than short rotation teak, which leads to improved dimensional stability. The higher volumetric swelling for the short rotation teak

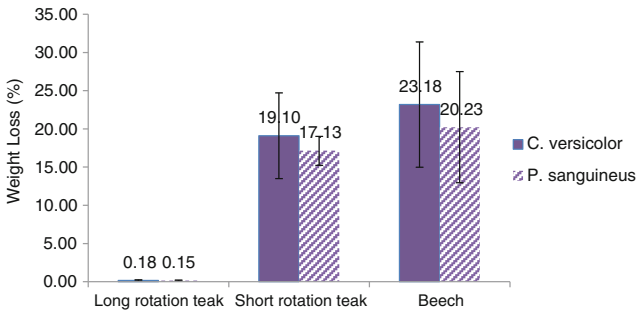


Fig. 5 Durability of short rotation and long rotation teak wood samples to white rot decay fungi

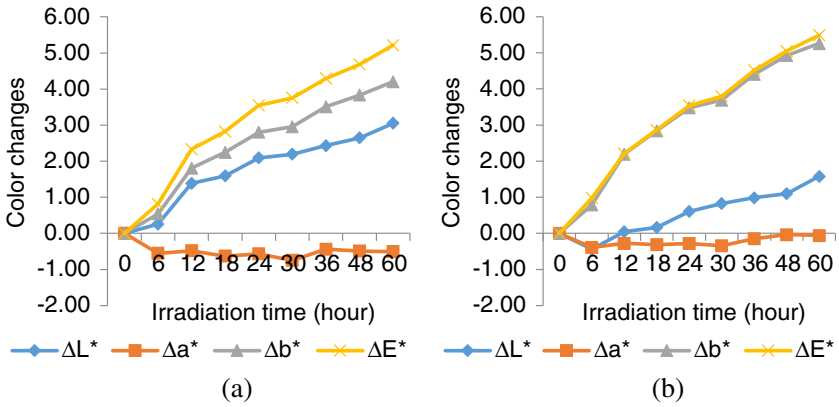


Fig. 6 Color stability at different irradiation times of long rotation teak (**a**) and short rotation teak woods (**b**)

suggests that careful attention should be given for the use of short rotation teak in some wood-processing technologies (e.g., production of sawn timber and drying, plywood, LVL…). This behavior may be correlated with lower extractive contents present in short rotation teak similar to the results described by Miller (1999) indicating that higher extractive contents in long rotation teak affect positively wood stability in changing moisture conditions. High extractive contents cause a decrease in the hygroscopic properties of some wood species; therefore, this may be one of the factors that led to an increase in the dimensional stability of wood (Skaar 1972).

4.6 Microscopic wood anatomy

Obvious differences were observed in the frequency of vessel elements between long and short rotations teak. Long rotation teak wood had lower vessel frequency (4.2 vessels/mm^2) compared to short rotation teak wood (5.5 vessels/mm^2) (Table 2). Martawijaya et al. (2005) found the vessel frequency of long rotation teak woods from 3 to 7 vessels/mm^2. Utomo (2006) also reports a vessel frequency for long rotation teak wood in the range 4 to 8 vessels/mm^2. This vessel frequency value is one of the important factor determining the dimensional stability and wettability of teak wood that affect the quality of wood. Lower vessel frequency tends to improve wood's dimensional stability. Therefore, long rotation teak had better dimensional stability than the short rotation teak.

4.7 MOE and MOR

Mean MOE values for long and short rotation teak wood calculated in this study were 12,861.8 and 9929.3 N/mm^2, respectively, and their mean MOR values were 118.9 and 97 N/mm^2, respectively (Table 2). Darmawan et al. (2015) found that the mean MOE values for long rotation teak and short rotation teak wood were 12,759 and 8323 N/mm^2, respectively, and their mean MOR values are 102 and 77 N/mm^2, respectively. Martawijaya et al. (2005) also found that the MOE and MOR of long rotation teak are 12,514 and 101 N/mm^2, respectively. Differences observed between long and short rotation teak wood are also in agreement with values reported by Hardiyanto and Prayitno (2006) on teak trees from several regions harvested at ages around 15–20 years indicating values MOE and MOR ranging from 83.4 to 119.4 and 6745.1 to 11,537.8 N/mm^2 for MOR and MOE, respectively. Miranda et al. (2011) reported that the mean MOE and MOR values of teak wood (50–70 years old) from East Timor are 10,684 and 141 N/mm^2, respectively. Kokutse et al. (2004) also reported that MOE value for 70 years teak is 16,704 N/mm^2. The juvenile core in trees is reported to be of lower density, lower stiffness (MOE) and strength (MOR), higher grain angle, higher longitudinal shrinkage, and higher incidence of reaction wood (Evans et al. 2000; Koubaa et al. 2005; Clark et al. 2006; Adamopoulos et al. 2007; Gryc et al. 2011; Lachenbruch et al. 2011). Bhat et al. (2001) characterized the juvenile wood of teak by wider rings, shorter fibers, smaller diameter and lower vessel percentage, higher cell wall percentage, and larger microfibril angle leading to lower mechanical properties. They concluded that the transition from juvenile to mature wood in teak lies somewhere around 20–25 years and the timber properties of juvenile wood including mechanical strength are comparable to the mature teak wood of 50–60 years. Several authors have also found that differences in mechanical and physical properties of juvenile wood and mature wood in teak were negligible (Baillères and Durand 2000). Thulasidas and Bhat (2012) stated that the short rotation teak was found to have strength properties similar to mature teak wood from forest plantation sites.

4.8 Brinell hardness

Martawijaya et al. (2005) found that the Brinell hardness mean value of long rotation teak was 41.3 N/mm^2. Wahyudi et al. (2014) also found that the Brinell hardness mean values of short rotation teak of 4 years old was 20.8 N/mm^2. The greater Brinell hardness values of long rotation teak wood were due to its higher density compared to short rotation teak wood

(Table 2). Dwianto and Marsoem (2008) reported that density of wood is one of the most important physical properties of wood that can affect the mechanical properties such as MOE and MOR.

4.9 Wettability

The results in Fig. 3 also indicate that extracted teak wood present higher wettability compared to teak woods with extractives. Higher contact angle for the wood with native extracts is considered to be caused by higher hydrophobicity and quantity of extractives present in the long rotation teak compared to short rotation teak (Simatupang et al. 1996). The long rotation teak contained higher fractions of low polarity compounds extracted with dichloromethane (Table 1). Nonpolar extractive compounds will reduce the ability on spreading and penetration of liquids into the wood surface.

4.10 Water sorption isotherm

The sorption curves were higher than the desorption curves for all samples. The changes in mass of the samples increased as the relative humidity increased. The changes in mass for the long rotation teak wood, either sorption or desorption cycles, were slightly lower than for the short rotation teak wood. This indicates that long rotation teak has absorbed less water compared to short rotation teak due to low vessel frequency in long rotation teak and higher extractive content. Various studies have shown that the extractive content play important role in the water sorption process. The presence of extractives in wood is reported to reduce EMC and lower change in mass (Wangaard and Granados 1967; Hernandez 2007).

4.11 Decay resistance

Higher decay resistance to fungi of long rotation teak was directly connected to its higher extractive content (Bhat et al. 2005). According to Tsoumis (1991), extractive content can affect the wood properties such as color and natural durability of wood. High contents of extractives are generally correlated with high natural durability against wood-destroying organisms. The high content of extractives in long rotation teak appears therefore responsible of wood durability. Miller (1999) stated that in some species, heartwood extractives make the wood resistant to fungi or insect attack. Nature and amounts of compounds present in wood extractives also affect the natural durability. The presence of large amount of tectoquinone in long rotation teak extracts increased its natural durability against wood-destroying organisms compared to the short rotation teak. Thulasidas and Bhat (2007) also noted that naphthoquinone and tectoquinone are responsible of teak resistance to brown-rot fungi. The absence of tectoquinone in the extractives of short rotation teak is probably the origin of the lower durability measured in our study.

4.12 Color changes

The ΔL^*, Δa^*, Δb^*, and ΔE^* of long rotation and short rotation teak wood increased during UV irradiation. The increase in Δb^* indicates lignin degradation during UV irradiation. This increase in the Δb^* value can be attributed to the formation of quinones and quinoide-like structures due to depolymerization and oxidation of lignin involving free radicals (Hon 2001). ΔL^* value of long rotation teak was more important than that of the short rotation teak, indicating that long rotation teak was more susceptible UV degradation compared to short rotation. The variation of extractives or chemical composition of lignin can explain the color variation of heartwood. For example, redness ($a*$) and lightness ($L*$) are correlated with extractive content, while yellowness ($b*$) is primarily related to the photochemistry of lignin (Gierlinger et al. 2004). Thulasidas et al. (2006) reported average values of 56.34, 6.85, and 23.44 for $L*$, $a*$, and $b*$, respectively, for heartwood from trees growing in plantations in India.

5 Conclusion

The results indicate that long rotation teak with higher heartwood content contains more extractives than short rotation teak wood containing mainly sapwood with high amount of juvenile wood. Tectoquinone was identified only in long rotation teak wood. The extractive contents affect directly the durability, dimensional stability, water sorption, and wettability of teak wood. Lower wood density and durability of the short rotation teak compared to the long rotation teak will restrict its utilization to some extent for both indoor and outdoor applications. Fast-growing teak from community cannot be used as usual heartwood teak from Perhutani because of the very low proportion of useful heartwood in the stem of fast-growing trees.

Acknowledgements The authors gratefully acknowledge the Ministry of Education and Culture Indonesia (BPKLN) and RISTEK DIKTI for the master degree scholarship of Dwi Erikan Rizanti and the "Ministère des Affaires Etrangères et du Développement International" (MAEDI) for its financial support through the Bio-Asie program. LERMAB is supported by a grant overseen by the French National Research Agency (ANR) as part of the "Investissements d'Avenir" program (ANR-11-LABX-0002-01. Lab of Excellence ARBRE).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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