

Characterization of *Tectona grandis* Extractives by GC-MS and IR and their Infusion into Rubberwood to Modify Dimensional Stability

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Teak (*Tectona grandis*) has been popularly known in the wood industry as a precious material due to its natural dimensional stability. To explore the main components affecting the dimensional stability of teak wood, the teak wood samples were extracted with different polar solvents, and the extractives were impregnated into rubberwood specimens to determine their effect on the dimensional stability of the modified rubberwood. The results showed that the methanol extractives of the teak wood exhibited the most significant effect on the dimensional stability of the rubberwood. The extractives were characterized by infrared (IR) and gas chromatograph/mass spectrum (GC/MS). The GC/MS results showed that the methanol extractives primarily contained 9,10-anthracenedione, 1,1-dimethyl-3,4-bis(1-methylethenyl), and alcohol compounds. It was speculated that the alcohol compounds in the methanol extractives reacted with polar hydroxyl groups in the cell wall, which resulted in a decrease in the size of the site combined with bound water. Moreover, the hydrophobic hydrocarbon compound was impregnated into rubberwood to form a thin layer of protective film in the cells into which the water could not enter under 20 °C and 80% RH.

Keywords: Dimensional stability; Extractives; GC-MS; Rubberwood; Teak

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INTRODUCTION

Teak (*Tectona grandis*) is considered a diadem of the tree species, and it grows naturally throughout southeastern Asia (Bhat *et al.* 2001; Xie *et al.* 2011). In China, teak has been planted in 7 provinces, latitude 18° to 26° 35' N and longitude 97° to 122 °E (Chen *et al.* 2000), and its plantation area is about 15,000 ha (Zhou *et al.* 2001). It is one of the most valuable tropical hardwood species on the international market (Sandermann 1966; Lourenco 2015). Teak wood from natural forests and plantations with long rotation ages has an established reputation due to its outstanding quality. It is prized for its beautiful texture, weather resistance, and high natural durability (Costa *et al.* 1958; Sandermann 1959), which make it suitable for different purposes including house construction, shipbuilding, furniture making, poles, veneer, and carvings (Romagnoli 2013).

The high natural durability of teak is an important characteristic that has been attributed to various compounds identified in the extractives of teak (Rudman *et al.* 1958; Lukmandaru *et al.* 2009). Several studies concerning the effect of the extractives content on the natural durability of teak have been published (Rudman *et al.* 1967, Lukmandaru *et al.* 2015). Quinones and their derivatives in the extractives of teak have been reported to defend against termite and fungal attack (Sumthong *et al.* 2006; Thulasidas *et al.* 2007;

Niamké 2011). The high decay resistance of teak heartwood is postulated to be due to a synergistic effect of the decay active ethanol extracts and caoutchouc (Sandermann 1964; Yamamoto *et al.* 1998).

Dimensional stability determines the use and variability of wood and is one of the important natural durability features of wood (Devi 2004; Pandey 2009). The dimensional stability could be related to the concentration of extractable substances in the wood (Kokutse 2004; Hernandez 2007; Roger *et al.* 2014). A dimensionally stable wood is one that shows small changes in size due to the changes in moisture.

In China, the rubber (*Hevea brasiliensis*) plantations are mainly located in Hainan, Yunnan, and Guangdong provinces. In 2008, the total rubber plantation area was approximately 776,000 ha (Zhao 2008). The rubber trees, which provide not only raw materials for the rubber industry but also abundant wood resources, are the main plantation tree species of the tropics. The main problem associated with using rubberwood is its dimensional instability due to moisture adsorption/desorption (Kokutse 2006). Because of the weak mechanical strength and dimensional instability, rubberwood is usually used to make furniture, which is generally limited to indoor applications. Chemical modification of the wood cell-wall polymers has been found to be effective in extending the service life and field of rubberwood (Rowell 2005; Jayashree 2012). Therefore, it is necessary to adopt the chemical modification methods to improve the value of rubberwood.

In previous literature, the durability of teak has been mainly attributed to the insecticidal properties and fungal resistance of the teak extractives (Bhat 2005; Thulasidas 2007; Kokutse *et al.* 2010), and the relationship between the dimensional stability and the teak extractives has not yet been investigated. The purpose of this study was to investigate the effect of the extractives of teak wood on wood's dimensional stability. A further goal was to identify and apply the main components affecting the dimensional stability of teak wood to modify rubberwood.

EXPERIMENTAL

Materials

Teak wood (heartwood and standard radial timber) that was free of knots and visible defects (Zhejiang Fudeli Wood Industry Co. Ltd., Shaoxing, China), was prepared to a size of 20 mm × 15 mm × 10 mm (R × T × L) wood blocks and wood powder (60-mesh). The wood powder was obtained using a FZ 102 pulverizer (Tianjin Taisite Instrument Co. Ltd., Tianjin, China). The teak wood blocks and teak powder were used for extraction. Rubberwood was collected from a 30-year-old rubber tree of rubber clone PR107 at Team 5 of the Experimental Farm of Chinese Academy of Tropical Agricultural Science, in Danzhou, from the Hainan province in China. The rubberwood was cut into boards 2.5 cm in the radial dimension from the logs, and the blocks without black streaks and knots were chosen for experiment.

The blocks were air-dried to have an equilibrium moisture content (EMC) in a continuously air-conditioned room before being split into pieces of 20 mm × 15 mm × 10 mm (R × T × L). Both the teak and rubberwood blocks were separated into many groups of seven longitudinally neighboring samples to perform dimensional stability tests.

Extraction of teak wood samples and impregnation of rubberwood samples

Methanol, ethyl acetate, petroleum ether, and the dichloromethane, which have a range of different polarities, were used as extraction solvents. They were of analytical grade and purchased from Guangzhou Chemical Reagent Co. Ltd. (Guangzhou, China). To extract the chemical components adequately, five out of the six groups of teak wood blocks were extracted continuously by using a Soxhlet extraction apparatus for 24 h until the reflux liquid became colorless. The final group was not extracted and used as a control. All of the teak wood powders (about 15 g) were extracted with the same aforesaid solvents. The obtained teak extractives were found to be different in color. They were then concentrated to the same volume (60 mL) by rotary evaporators and impregnated into rubberwood blocks.

Three out of the four groups of the rubberwood blocks were placed in the beakers containing the teak wood extractives of different solvents (the methanol, petroleum ether, ultrapure water). Then they were kept in a vacuum-pressure tank for 40 min under 1.4 MPa pressure. The rubberwood blocks were then taken out from the beakers and the liquid on the surface of all the blocks was removed with a clean dry cloth. The rubber specimens were kept air-dried at room temperature. The final group was left untreated as a control. The rubberwood was impregnated once and thrice to compare the effect of different amounts of the teak extractives on the dimensional stability of rubberwood.

Methods*Determination of dimensional stability and adsorption*

After extraction, the teak wood blocks (five groups, every group contained seven wood blocks) were stored and air-dried at room temperature for three days. All of the extracted and non-extracted wood blocks were then kept in oven at 60 °C until they were deemed to have reached the EMC. The samples were weighed (W_0) on a 0.0001 g precision balance and measured with 0.01 mm precision in the radial (R_0) and tangential (T_0) directions. The wood blocks were conditioned at 20 °C and 80% relative humidity (RH) until the EMC was reached, after which the humid mass (W_H), humid radial (R_H), and humid tangential (T_H) dimensions were obtained in the same way. The determination of the dimensional change (D) was determined as follows (Royer *et al.* 2010),

$$D = \frac{R_H \times T_H - R_0 \times T_0}{R_0 \times T_0} \times 100 \quad (1)$$

whereas the moisture content (MC) was calculated as follows:

$$MC = \frac{W_H - W_0}{W_0} \times 100 \quad (2)$$

The calculation of the dimensional change of the impregnated rubberwood blocks was similar with that of the extracted teak wood blocks.

After being impregnated, the rubberwood was taken out and immediately weighed on an analytical balance at a 0.0001 g precision to get m_1 . The weight of rubberwood under absolute dry was m_0 . The adsorption amount (A) was determined as follows,

$$A = \frac{m_1 - m_0}{m_0} \times 100 \quad (3)$$

Characterization of Teak Wood Extractives

Fourier transformed infrared (FTIR) analysis of the teak wood extractives were performed on a Thermo Scientific Nicolet iN10 IR spectrometer (Thermo Nicolet Co.,

Ltd., Massachusetts, USA) by dispersing samples in potassium bromide. The number of scans was 500 to 4000 cm^{-1} , and the resolution is 0.4 cm^{-1} . The percentage of mass of sample and KBr used in FTIR was 1:100, and the mass of sample was 0.001g.

The gas chromatography/mass spectrum (GC/MS) determination of the teak wood extractives was performed using a Shimadzu GC MS-QP2010 Ultra (Shimadzu Co., Ltd., Kyoto, Japan). An elastic quartz capillary column Rtx-5ms (30 $\mu\text{m} \times 250 \mu\text{m} \times 0.25 \mu\text{m}$) coated with a neutral phase was used. The injection port temperature was 300 $^{\circ}\text{C}$, and the carrier gas was helium. The temperature program of GC began at 60 $^{\circ}\text{C}$ (3 min) and increased at the rate of 20 $^{\circ}\text{C}/\text{min}$ until 200 $^{\circ}\text{C}$, and 5 $^{\circ}\text{C}/\text{min}$ until 300 $^{\circ}\text{C}$ (10 min) was reached, followed by a splitless injection. The program of Mass Spectrometer (MS) was scanned over the 1.5 AMU to 1090 AMU (m/z), with an ionizing voltage of 70 eV and an ionization current of 150 μA of electron ionization. The ion source temperature was 230 $^{\circ}\text{C}$, the quadropole temperature was 150 $^{\circ}\text{C}$, and the flow velocity of helium was 1.4 mL/min.

Light microscopy

To observe the change of extracted teak wood and the distribution of the extractives impregnated in rubberwood, the rubberwood samples were cut by slicer along the radial direction and tangential direction, respectively. Then the wood slices were observed under a Leica DMLB microscope (Leica, Wetzlar, Germany).

RESULTS AND DISCUSSION

Determination of Dimensional Stability of Extracted Teak Wood

After the teak wood blocks were extracted with different solvents and conditioned at 20 $^{\circ}\text{C}$ and 80% RH, the change in the moisture content was measured and compared with that of the non-extracted wood pieces as a control (see Fig. 1).

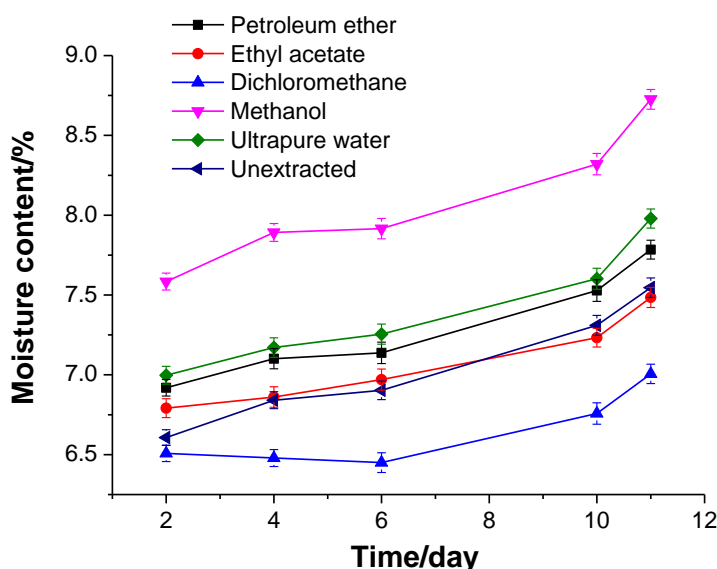


Fig. 1. Change of the moisture content of teak wood after being extracted with different solvents and conditioned at 20 $^{\circ}\text{C}$ and 80% RH

The moisture content of all five groups of the extracted teak wood increased with time. In Fig. 1, the teak wood extracted with methanol exhibited a higher change of moisture content than the samples from both the non-extracted and the other solvents extracted. The moisture content of the teak wood blocks extracted with methanol increased from 7.58% to 8.73% at 20 °C and 80% RH. The moisture of the specimens extracted with ultrapure water was enhanced 0.98%, while those extracted by petroleum ether increased 0.87%. It was presumable that the methanol extraction removed more polar hydroxyl group compounds, and that more sorption sites were available for the bound water. This result was consistent with the phenomenon reported by Royer (2010).

The influence of the solvent extraction, compared to no extraction, on the dimensional stability is given in Fig. 2. At the beginning, the teak wood blocks extracted with the ultrapure water showed a higher swelling speed than those extracted with methanol, which eventually increased to 5.29%. The dimensional change of the teak wood blocks extracted with the ultrapure water rose from 4.42% to 4.97%, and those extracted with dichloromethane increased by 0.59%. The results showed that the samples extracted with methanol displayed remarkably greater swelling than the non-extracted and those extracted with other solvents. The result was similar to the change in moisture content shown in Fig. 1.

It was observed that the dimensional stability of the teak wood samples extracted with the methanol, ultrapure water, or petroleum ether became lower and that the methanol could extract a higher amount of extractives, which were responsible for dimensional stability. Moreover, it was confirmed that the dimensional stability was proportional to the content of the extractives. In this context, it was speculated that these wood extractives soluble in methanol were likely to associate with the cell wall in the amorphous regions of the macromolecules network, thereby contributing to the supra-molecular organization of the network and competing with water adsorption (Shupe *et al.* 1996).

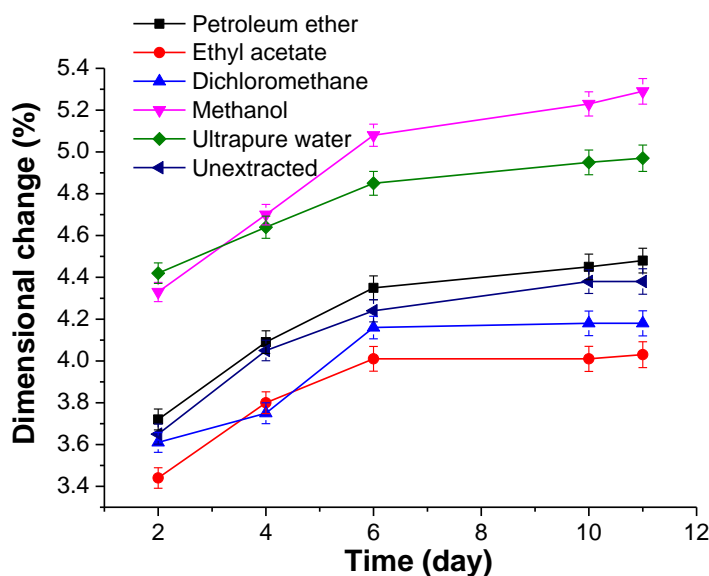


Fig. 2. The change of dimensional stability of the teak wood after being extracted with different solvents and conditioned at 20 °C and 80% RH

Determination of Dimensional Stability of Rubberwood Impregnated with Teak Wood Extractives

To further investigate the impact of the teak wood extractives on the dimensional stability, the teak wood extractives were impregnated into rubberwood. The effect of teak extractives on the dimensional stability of rubberwood is presented in Fig. 3 (green). A dimensionally stable wood is one that shows small changes in size due to the changes in moisture. The dimensional change of untreated rubberwood was 4.60%, while the dimensional change of the rubberwood treated with the teak wood extractives was clearly smaller under 20 °C and 80% RH than that of the untreated, which exhibited higher changes in dimensions.

The rubberwood that was impregnated with methanol extractives had the smaller dimensional change (4.05%). Using the different solvents selected for this study, the extractions yielded contrasting effects on the dimensional stability of teak samples. Similarly, the impregnation of the resulting extractives resulted in contrasting effects on the dimensional stability of rubberwood samples. This may have been attributable to the fact that the different solvents removed different combinations of chemicals from the wood (see Table 2). It was speculated that the extractives obtained by methanol were combined more easily with the polar hydroxyl groups in the cell wall of rubberwood. When all of the rubberwood that was impregnated with the extractives was placed under 20 °C and 80% RH, fewer sorption sites of the rubberwood impregnated with methanol extractives were available for the bound water. The rubberwood treated with the methanol extractives exhibited better dimensional stability.

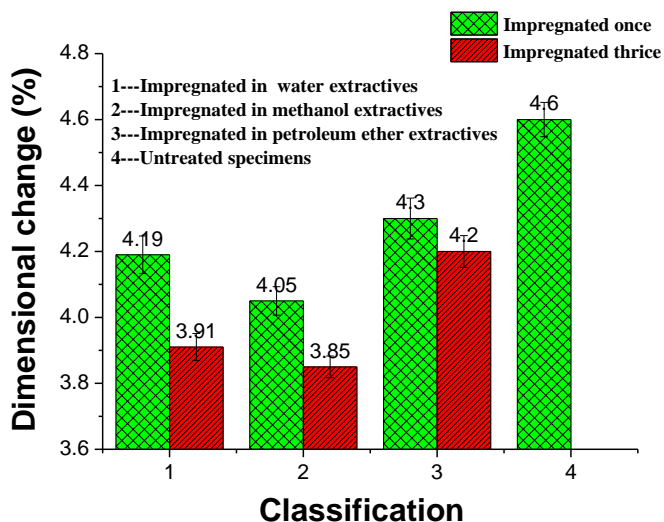


Fig. 3. The dimensional changes of rubberwood impregnated once or thrice and conditioned at 20 °C and 80% RH until constant moisture.

The adsorption performance of rubberwood that was impregnated once or thrice is presented in Table 1. The rubberwood treated with the ultrapure water extractives had similar adsorption to that infused with the methanol extractives. The boiling point of methanol is low and easy to volatilize, and the weight of the rubberwood impregnated with methanol extractives was relatively lower. Compared to the rubberwood impregnated once, the amount of adsorption of rubberwood impregnated thrice with ultrapure water extractives became larger, rising from 80.39% to 82.56%, and the standard deviation was 3.43%.

The rubberwood was impregnated once or thrice to investigate the impact of the concentration of the extractives on improving the dimensional stability of rubberwood (Fig. 3 red). When the concentration of extractives increased, the dimensional change of the rubberwood treated with water extractives became smaller and declined from 4.19% to 3.91%, whereas those treated with methanol declined to 3.85%. From the measured dimensional change, it was seen that the rubberwood impregnated thrice exhibited smaller swelling than that which was impregnated once. While the amount of adsorption of rubberwood impregnated thrice was larger than that impregnated once, such as the amount of adsorption of rubberwood impregnated with methanol extractives increased from 77.97% to 81.05%. Therefore, it was confirmed that the more the concentration of extractives increased, the lower was the dimensional change of treated rubberwood.

Table 1. Adsorption of Rubberwood Impregnated with Different Teak Extractives, Once or Thrice (n=7)

Teak Extractives	Adsorption (A)	
	Impregnated Once (%)	Impregnated Thrice (%)
Ultrapure water extractives	80.39(3.78)	82.56(3.43)
Methanol extractives	77.97(4.82)	81.05(4.38)

IR Characterization of Teak Wood Extractives

The Infrared (IR) characterization of teak extractives extracted with petroleum ether, dichloromethane, methanol, and ultrapure water is presented in Fig.4. It can be seen that the IR spectra of the extractives of petroleum ether, dichloromethane, and ethyl acetate were similar, because these solvents shared a similar polarity. The characteristic bands at 3400 cm^{-1} (-OH stretching vibration), 2908 cm^{-1} (C-H stretching vibration), 1619 cm^{-1} (-OH bending), and 1738 cm^{-1} (-C=O stretching) were prominent and appeared in all of the IR spectra (Pandey *et al.* 2009, Li *et al.* 2015).

The difference was mainly distributed in the fingerprint region. The band at 1125 cm^{-1} (-C-O- stretching vibration) was much more prominent in the methanol and ultrapure water extractives due to the involvement of the extractive like alcohol compounds. The band at 3400 cm^{-1} (-OH stretching vibration) in the methanol and ultrapure water extractives was stronger and the more hydroxyl compounds were extracted. The bands at 1450 cm^{-1} (-CH₂- bending vibration) and 2960 cm^{-1} (-CH₃ and -CH₂- stretching vibration) in dichloromethane extractives, ethyl acetate extractives, methanol extractives and petroleum ether extractives were more obvious, so the extractives contained more alkane compounds.

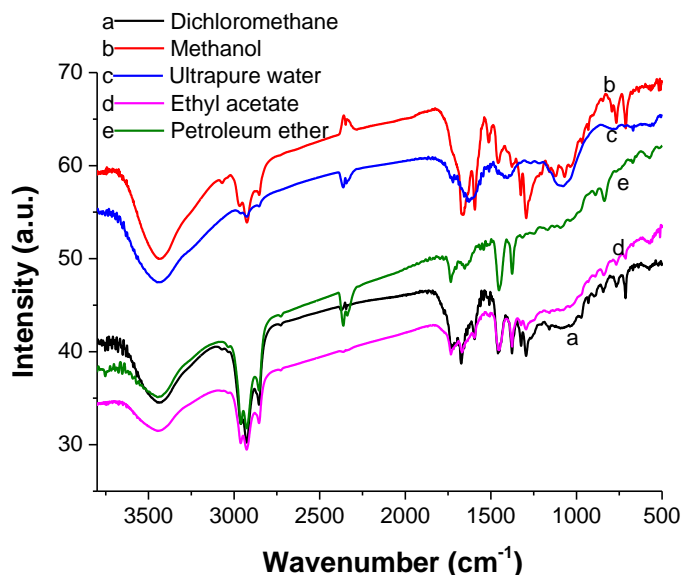


Fig. 4. The IR spectra of different extractives of teak wood

GC-MS Characterization of Teak Wood Extractives

The dimensional stability of the rubberwood samples impregnated in the methanol, ultrapure water, or petroleum ether extractives was clearly improved, while the dimensional stability of the teak wood blocks extracted with the methanol, ultrapure water, and petroleum ether were dramatically reduced. Therefore the methanol, ultrapure water, and petroleum ether extractives were characterized by the GC-MS (see Figs. 5 through 7). The main components in the teak wood extractives are presented in Table 2.

The main components in the teak wood extracts extracted with the ultrapure water were carboxylic acids (67.4%), whose polarity was similar with that of the water, and the retention time mainly ranged from 18.51 min to 23.69 min. The most abundant compound in the petroleum ether extractives was 1,1-dimethyl-2,4-bis (1-methylethenyl) at 50.6%. The methanol extractives primarily contained 9,10-anthracenedione (13.8%), 1,1-dimethyl-3,4-bis (1-methylethenyl) (30.1%), and alcohol compounds (26.6%). The intermediate polarity of methanol made it capable of extracting compounds that were usually insoluble in the ultrapure water or less polar solvents.

The rubberwood samples impregnated in the methanol extractives of the teak wood exhibited higher dimensional stability than those impregnated in the ultrapure water or petroleum ether extractives. The good abrasion resistance and durability properties of teak wood are often associated with the occurrence of caoutchouc (Sandermann *et al.* 1966). It was reported that petroleum ether can remove the hydrophobic caoutchouc (Yamamoto *et al.* 1998), but in this study the teak wood extracted with petroleum ether did not exhibit the weakest dimensional stability, the teak wood extracted with methanol presented the weakest dimensional stability.

It was speculated that the alcohol compounds in the methanol extractives may have associated with the polar hydroxyl groups in the cell wall and reduced the size of the site that can be combined with bound water. Also, that the hydrophobic hydrocarbon compound that was impregnated into the rubberwood to form a thin layer of protective film in the cells into which the water could not enter under 20 °C and 80% RH. Thus, it was confirmed that the dimensional stability was proportional to the content of the teak wood extractives.

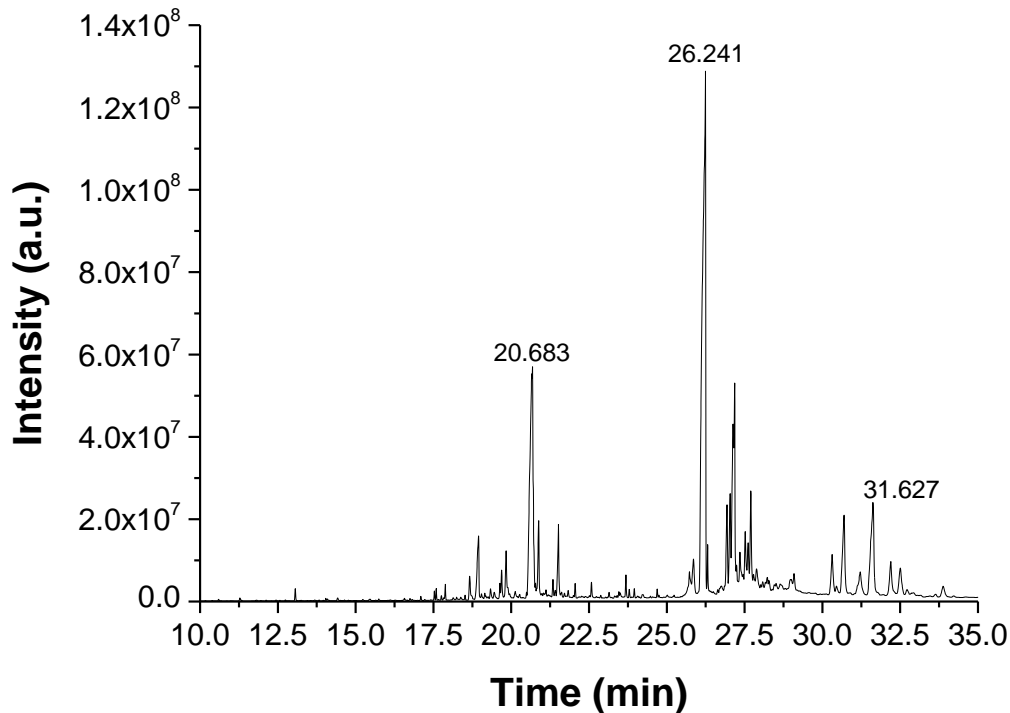


Fig. 5. The GC-MS spectra of the methanol extractives of teak wood

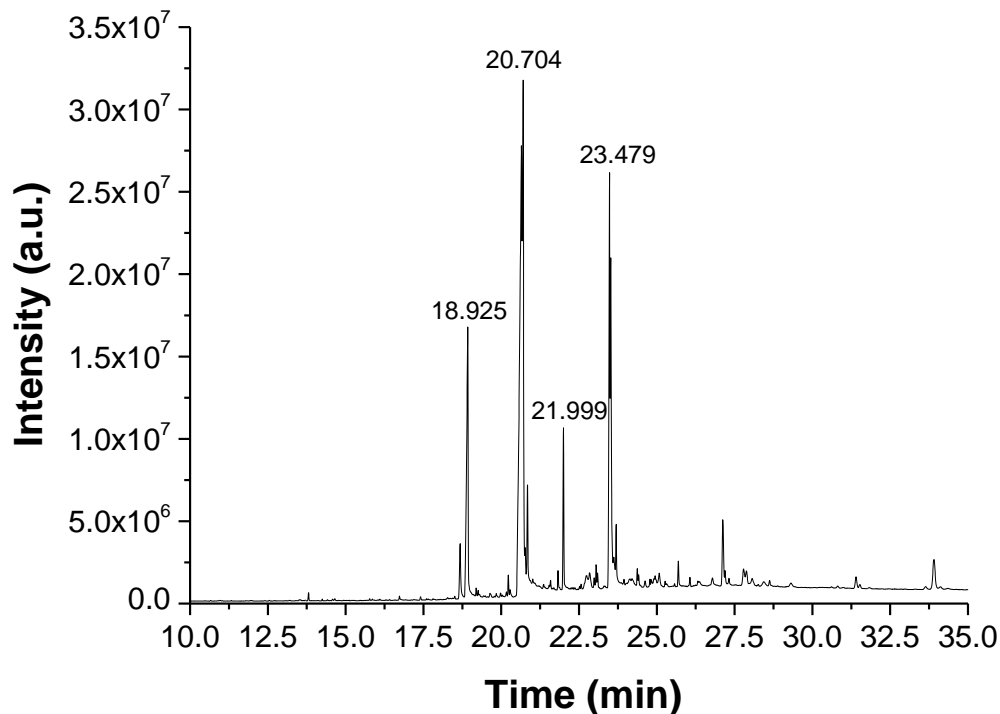


Fig. 6. The GC-MS spectra of the ultrapure water extractives of teak wood

Table 2. The Main Chemical Components in the Teak Extractives

No.	RT (min)	Name of Component	Methanol Extractives	Water Extractives	Petroleum Ether Extractives
1	18.679	9-Hexadecenoic acid	-	1.8	-
2	18.685	2-Hydroxy-10H-acridin-9-one	-	1.5	-
3	18.883	1,2-Benzenedicarboxylic acid, dibutyl ester	-	4.9	-
4	18.925	n-Hexadecanoic acid	1.9	10.7	-
5	19.82	[1,1'-Biphenyl]-2-ol, 5-(1,1-dimethylethyl)-	-	-	3.3
6	20.574	9,10-Anthracenedione, 2-methyl-	13.8	-	4.3
7	20.608	cis-Vaccenic acid	-	-	1.5
8	20.649	9,12-Octadecadienoic acid (Z,Z)-	-	28.0	-
9	20.704	cis-Vaccenic acid	-	15.7	-
10	20.843	Octadecanoic acid	1.7	2.6	1.1
11	21.518	Oxacycloheptadec-8-en-2-one, (8Z)	1.6	-	1.1
12	21.999	15-Hydroxypentadecanoic acid	-	4.7	-
13	23.479	9,12-Octadecadienoyl chloride, (Z,Z)-	-	10.8	-
14	23.519	cis-11-Hexadecenal	-	8.6	-
15	25.856	Squalene	1.1	0.7	-
16	26.198	1,1-dimethyl-2,4-bis(1-methylethenyl), cis-	-	-	50.6
17	26.241	3,4-bis(1-methylethenyl)-1,1-dimethyl	30.1	-	-
18	27.008	Tetracosahexaen-3-ol #	-	-	2.2
19	27.036	2,2-dimethyl-3-(3,7,12,16,20-pentamethyl-3,7,11,15,19-heneicosapentaenyl)-, Oxirane,	6.7	-	0.5
20	27.078	Farnesolisomera	-	-	2.8
21	27.121	9,12-Octadecadienoic acid, methyl ester	-	2.3	-
22	27.121	Hexadeca-2,6,10,14-tetraen-1-ol, 3,7,11,16-tetramethyl-	-	-	2.6
23	27.181	trans-Geranylgeraniol	14.3	-	-
24	30.315	Campesterol	1.5	-	-
25	30.606	Stigmasta-5,22-dien-3-ol	-	-	2.1
26	31.159	Ergosta-8,24(28)-dien-3-ol, 4,14-Dimethyl-	-	-	1.4
27	30.699	Stigmasterol	3.4	-	-
28	31.5	Stigmast-5-en-3-ol, (3.beta.,24s)-	1.3	-	3.2
29	31.627	gamma-Sitosterol	5.4	0.8	-
30	32.2	9,19-Cycloergost-24(28)-en-3-ol, 4,14-dimethyl-, acetate	1.5	-	1.4
31	33.909	Z,Z-6,24-Tritriacontadien-2-one	-	1.7	-

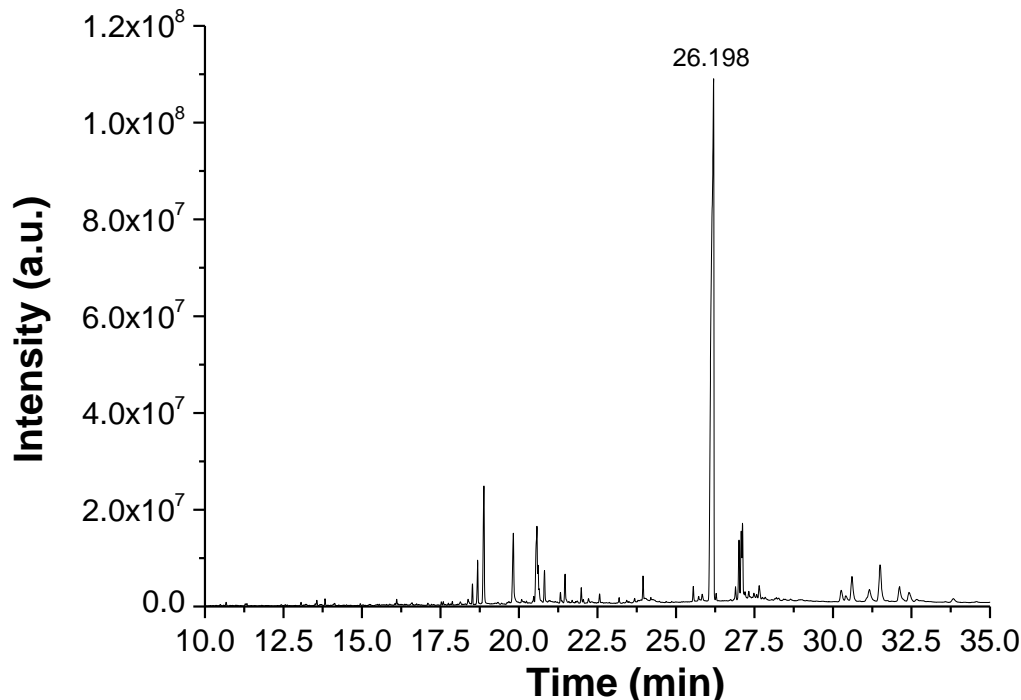


Fig. 7. The GC-MS spectra of petroleum ether extractives of teak wood

Light Microscopy Analysis of Teak Wood Extracted by Methanol and Rubberwood Impregnated in Methanol Extractives

To compare the change between the teak wood extracted by methanol and untreated teak wood, their microstructures in tangential direction were observed under light microscopy, and the results are shown in Figs. 8a and b. It was found that the cell cavities of teak wood extracted by methanol were almost vacant (red arrow). The color of untreated teak wood was obvious deeper yellow and the extractives were distributed on the cell wall.

The microstructures in radial direction of rubberwood, which included rubberwood impregnated in teak wood's methanol extractives and untreated rubberwood, are presented in Figs. 8c and d. Compared to the untreated rubberwood, the yellow extractives were distributed on the cell wall of rubberwood impregnated in extractives and red arrows showed the methanol extractives.

The transparent balls appearing in the micrographs of rubberwood represent starch, the content of which is very rich in rubberwood. As a consequence, rubberwood is easily susceptible to mildew and must be modified to make it suitable for various applications. The cell wall of untreated rubberwood was empty (red arrow), and it did not have the yellow substance. It was concluded that the methanol extractives of teak wood were distributed on the cell wall of the impregnated rubberwood.

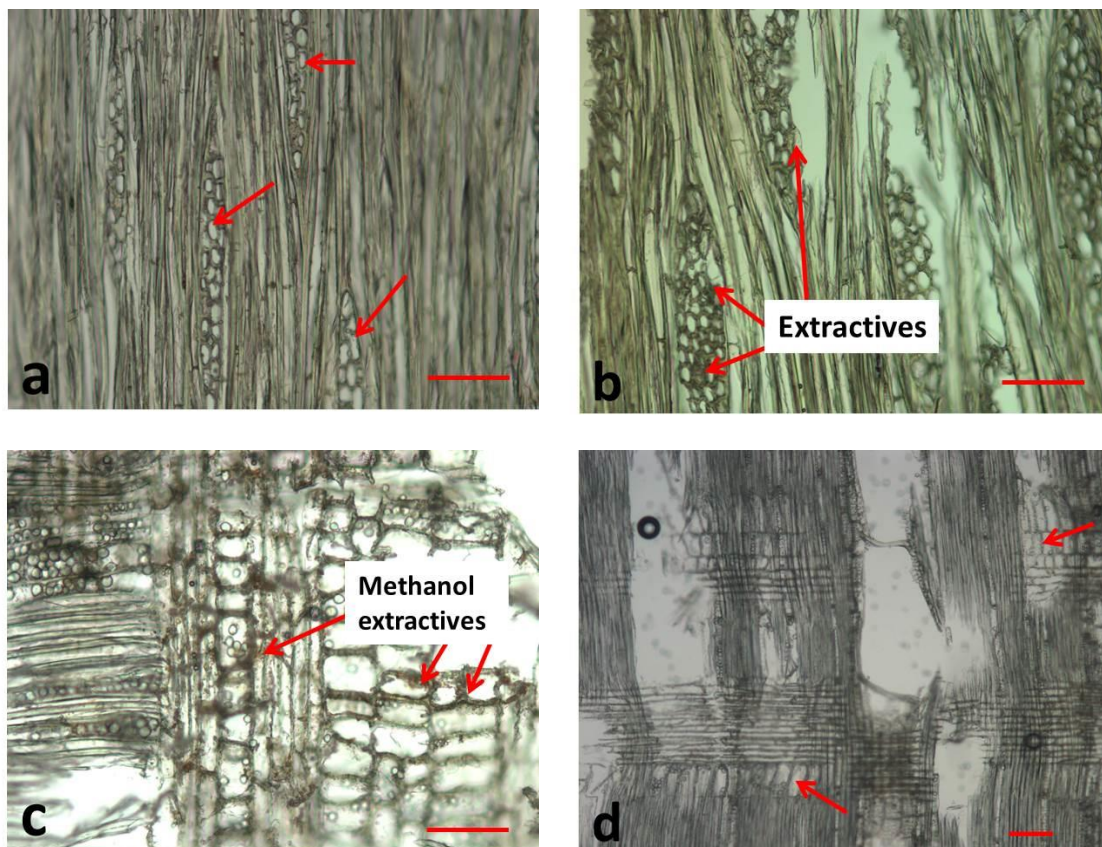


Fig. 8. Light micrographs of teak wood samples in tangential direction and rubberwood samples in radial direction. (a) Teak wood extracted by methanol. (b) Untreated teak wood. (c) Rubberwood impregnated in teak wood's methanol extractives. (d) Untreated rubberwood. Bars = 100 μm . Red arrows show the distinct difference.

CONCLUSIONS

1. The teak wood extracted with methanol exhibited much greater dimensional change under 20 °C and 80% RH compared to the non-extracted and those extracted with other solvents.
2. When the methanol, ultrapure water, and petroleum ether extractives of the teak wood were impregnated into rubberwood, the rubberwood samples impregnated with the methanol extractives showed less swelling under the hydrothermal conditions than the non-extracted specimens and those impregnated with other extractives, and they also manifested higher dimensional stability.
3. The GC-MS analysis showed that the methanol extractives primarily contained 9,10-anthracenedione (13.8%), 1,1-dimethyl-3,4-bis (1-methylethenyl)- (30.1%), and alcohol compounds (26.6%).
4. Results of this study suggest that it is feasible to extract the teak wood and prepare wood modifiers *via* chemical methods to improve the dimensional stability of other woods in the future.

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REFERENCES CITED

- Bhat, K. M., Priya, P. B., and Rugmini, P. (2001). "Characterisation of juvenile wood in teak," *Wood Science and Technology* 34(6), 517-532. DOI: 10.1007/s002260000067
- Bhat, K. M., Thulasidas, P. K., Ejm, F., and Jayaraman K. (2005). "Wood durability of home-garden teak against brown-rot and white-rot fungi," *Trees* 19(6), 654-660. DOI: 10.1007/s00468-005-0429-0
- Chen, C. J., and Chen, H. F. (2000). *Cultivation of Broad-leaved Tree*, China Forest Publication, Beijing, China.
- Costa, E., Rudman, P., and Gay, F. J. (1958). "Investigations on the durability of *Tectona grandis*," *Empire Forestry Review* 37(3), 291-298.
- Devi, R. R., Maji, T. K., and Banerjee, A. N. (2004). Studies on dimensional stability and thermal properties of rubberwood chemically modified with styrene and glycidylmethacrylate," *Journal of Applied Polymer Science* 93(4), 1938-1945. DOI: 10.1002/app.20657
- Hernandez, R. E. (2007). "Swelling properties of hardwoods as affected by their extraneous substances, wood density, and interlocked grain," *Wood and Fiber Science* 39(1), 146158.
- Jayashree S., Krishna K. P., Prakash, G. K., and Mahadevan, K. M. (2012). "Photo bleaching and dimensional stability of rubber wood esterified by fatty acid chlorides," *Journal of Wood Chemistry and Technology* 32(2), 121-136. DOI: 10.1080/02773813.2011.624665
- Kokutse, A. D., Baillères, H., Stokes, A., and Kokou, K. (2004). "Proportion and quality of heartwood in Togolese teak (*Tectona grandis* L.f.)," *Forest Ecology and Management* 189(1-3), 37-48. DOI: 10.1016/j.foreco.2003.07.041
- Kokutse, A. D., Stokes, A., Bailleres, H., Kokou, K., and Baudasse, C. (2006). "Decay resistance of Togolese Teak (*Tectona grandis*) heartwood and relationship with colour," *Trees* 20(2), 219-223. DOI: 10.1007/s00468-005-0028-0
- Kokutse, A. D., Stokes, A., Kokutse, N. K., and Kokou, K. (2010). "Which factors most influence heartwood distribution and radial growth in plantation teak," *Annals of Forest Science* 67(4), 407-407. DOI: 10.1051/forest/2009127
- Lukmandaru, G., and Takahashi, K. (2009). "Radial distribution of quinones in plantation teak (*Tectona grandis* L.f.)," *Annals of Forest Science* 66(6), 605-613. DOI: 10.1051/forest/2009051
- Lourenco, A., Neiv, D. M., Gominho, J., Marques, A. V., and Pereira, H. (2015). "Characterization of lignin in heartwood, sapwood and bark from *Tectona grandis* using Py-GC-MS/FID," *Wood Science and Technology* 49(1), 159-175. DOI: 10.1007/s00226-014-0684-6
- Lukmandaru, G. (2015). "Chemical characteristics of teak wood attacked by neotermestectonae," *BioResources* 10(2), 2094-2102. DOI: 10.15376/biores.10.2.2094-2102

- Li, M. Y., Cheng, S. C., Li, D., Wang, S. N., and Huang, A. M. (2015). "Structural characterization of steam-heat treated *Tectona grandis* wood analyzed by FT-IR and 2D-IR correlation spectroscopy," *Chinese Chemical Letters* 26(2), 221-225. DOI: 10.1016/j.ccllet.2014.11.024
- Niamké, F. B., Amusant, N., Charpentier, J. P., Chaix, G. C., Baissac, Y., Boutahar, N., Adima, A. A., Coulibaly, S. K., and Allemand, C. J. (2011). "Relationships between biochemical attributes (non-structural carbohydrates and phenolics) and natural durability against fungi in dry teak wood (*Tectona grandis* L. f.)," *Annals of Forest Science* 68(1), 201-211. DOI: 10.1007/s13595-011-0021-2
- Pandey, K. K., Jayashree H. C., and Nagaveni (2009). "Study of dimensional stability, decay resistance, and light stability of phenylisothiocyanate modified rubberwood," *BioResources* 4(1), 257-267.
- Roger M., Bond, B., and Quesada, H. (2014). "A review of heartwood properties of *Tectona grandis* trees from fast-growth plantations," *Wood Science and Technology* 48(2), 411-433. DOI: 10.1007/s00226-014-0618-3
- Royer, M., Stien, D., Beauchêne, J., Herbette, G., Mclean, J. P., Thibaut, A., and Thibaut, B. (2010). "Extractives of the tropical wood wallaba (*Eperua falcate* Aubl.) as natural anti-swelling agents," *Holzforschung* 64(2), 211-215. DOI: 10.1515/HF.2010.034
- Romagnoli, M., Segoloni, E., Luna, M., Margaritelli, A., Gatti, M., Santamaria, U., and Vinciguerra, V. (2013). "Wood colour in Lapacho (*Tabebuia ratifolia*): Chemical composition and industrial implications," *Wood Science and Technology* 47(4), 701-716. DOI: 10.1007/s00226-013-0534-y
- Rudman, P., Costa, E., Gay, F. J., and Wetherly, A. H. (1958). "Relationship of tectoquinone to durability in *Tectona grandis*," *Nature* 181(4610), 721-722. DOI: 10.1038/181721b0
- Rudman, P., Costa, E., and Gay, F. J. (1967). "Wood quality in plus trees of teak (*Tectona grandis* L.f.): An assessment of decay and termite resistance," *Sylvae Genet* 16, 102-105.
- Rowell, R. M. (2005). *Handbook of Wood Chemistry and Wood Composite*, CRC Press, Boca Raton, FL, pp. 381-420.
- Sandermann, W., and Dietrichs, H. H. (1959). "Chemische Untersuchungen an Teakholz," *Holzforschung* 13(5), 137-148. DOI: 10.1515/hfsg.1959.13.5.137
- Sandermann, W., and Simatupang, M. H. (1964). "The ingredients from teak (*Tectona grandis* L.), II. Constitution and synthesis of the tectols and dehydrotectols," *European Journal of Inorganic Chemistry* 97(2), 588-597. DOI: 10.1002/cber.19640970240
- Sandermann, W., and Simatupang, M. H. (1966). "The chemistry and biochemistry of teak wood (*Tectona grandis* L.)," *European Journal of Wood and Wood Products* 24(5), 190-204. DOI: 10.1007/BF02610269
- Shupe, T. F., Choong, E. T., and Gibson, M. D. (1996). "The effects of previous drying and extractives on the radial and tangential shrinkage of outerwood, middlewood, and corewood of two sweetgum trees," *Forest Products Journal* 46(9), 94-97.
- Sumthong, P., Damveld, R. A., Choi, Y. H., Arentshorst, M., Ram, A. F. J., Vanden Honde, C. A., and Verpoorte, R. (2006). "Activity of quinones from teak (*Tectona grandis*) on fungal cell wall stress," *Planta Medica* 72(10), 943-944. DOI: 10.1055/s-2006-946676

- Thulasidas, P. K., and Bhat, K. M. (2007). "Chemical extractive compounds determining the brown-rot decay resistance of teak wood," *European Journal of Wood and Wood Products* 65(2), 121-124. DOI: 10.1007/s00107-006-0127-7
- Xie, C. P., Li, K. F., Lin, J. L., and Li, J. B. (2011). "GC-MS analysis on heartwood extractive chemical components of different provenances teak (*Tectona grandis* L.f)," *Advanced Materials Research* 236-238, 1049-1053. DOI: 10.4028/www.scientific.net/AMR.236-238.10497
- Yamamoto, K., Simatupang, M. H., and Hashim, R. (1998). "Caoutchouc in teak wood (*Tectona grandis* L. f.): Formation, location, influence on sunlight irradiation, hydrophobicity and decay resistance," *European Journal of Wood and Wood Products* 56(3), 201-209. DOI: 10.1007/s001070050299
- Zhao, Y. K. (2008). *Promotion of Rubberwood Processing Technology in the Asia-Pacific Region*, Chinese Research Institute of Wood Industry Publication, Haikou, China.
- Zhou, T. F. (2001). *Cultivation Technology of Tropical Main Economy Forestry in China*, China Forest Publication, Beijing, China.

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