Journal of Renewable Materials

Tech Science Press

DOI: 10.32604/jrm.2021.016089

ARTICLE

Structure, Dynamic-Mechanical and Acoustic Properties of Oil Palm Trunk Modified by Melamine Formaldehyde

Tetti Novalina Manik[1,2,*], Sulung Apria Nuki[2], Nur Aini Fauziyah[1], Mashuri[1], Mochamad Zainuri[1] and Darminto[1,*]

[1]Department of Physics, Faculty of Science and Data Analytics, Institut Teknologi Sepuluh Nopember, Surabaya, 60111, Indonesia

[2]Physics Study Program, Faculty of Mathematics and Natural Sciences, Universitas Lambung Mangkurat, Banjarbaru, 70714, Indonesia

[*]Corresponding Authors: Tetti Novalina Manik. Email: tetti.manik@ulm.ac.id; Darminto. Email: darminto@physics.its.ac.id

Received: 05 February 2021 Accepted: 23 February 2021

ABSTRACT

The performance of oil palm trunk wastes from Banjarbaru of South Kalimantan was improved with the help of chemical modification in a two-step treatment. The first was formalization with formaldehyde solution with varying pH, and the second was impregnation with melamine-formaldehyde resin under 5 bar pressure for an hour. In these processes, the samples were cured at 120°C for 10 min and then dried in an oven at (103 ± 2)°C in order to attain a moisture content of less than 6%. These treatments improved the physical properties (density, moisture content, and volume swelling), mechanical resistance, dynamic-mechanical and acoustic performance of the woods. The combination of impregnation and formalization changed the structure and the morphology of the woods such that the surface became flatter and denser. This was confirmed by results from FTIR, SEM, and DMA. Samples with alkaline modification displayed the best results for dimensional stability, storage modulus, and damping factor in varied frequencies. The treatments in this study also heightened acoustic performances as evidenced by the resulting characteristics of sound absorption coefficient and acoustic impedance.

KEYWORDS

Acoustic performances; dynamic-mechanical; formalization; oil palm trunk

1 Introduction

Wood can be regarded as a composite material, consisting of cellulose as the reinforcer and hemicellulose and lignin as matrix. Cellulose is responsible for the stiffness of wood, while the matrix is responsible for the viscoelasticity and volume swelling. Reinforcement and matrixes are associated with hydrogen and covalent bonds, which impact the hygroscopicity and dimensional instability of wood [1]. Usually, wood boards of good quality contain minimum lignin and hemicellulose. They are amorphous heteropolymers that influence the hardness of wood, the impermeability, and susceptibility to microbiological disorders and have a high water content [2]. The modification of lignin using other polymeric materials is performed to change the structure of the wood, improve its quality, and enhance its performance. Formaldehyde compounds constitute one of the polymeric materials used in this study to form cross bonds with O–H groups in wood cell walls. Wood can react with formaldehyde (CH_2O) strongly if a catalyst is added. The pH level of the formaldehyde solution affects the reduction of the amount of O–H group binding in the wood structure [3,4].

An improvement of physical and mechanical properties as well as dimensional stability by impregnating the cell walls of wood by melamine-formaldehyde (MF) resin [5–9] has been carried out on pine and spruce wood [5,7,9]. The impregnation reduces the hygroscopic properties of wood, as water molecules in the structure of the wood get replaced by the polymeric material of the MF resin. Therefore, the dimensional stability of wood becomes more resistant to environmental conditions. MF resin is also less expensive than phenol-formaldehyde resins. Moreover, it has high hardness and stiffness, higher water resistance than urea-formaldehyde, and low flammability [7]. The most important is the amino resin, which is non-toxic when used at temperatures below 100°C, as the formaldehyde in the resin evaporates above that temperature [10].

Indonesia is the largest oil palm producer in the world. After 25–30 years of production, oil palm plants enter the replanting period and produce a lot of waste. Oil palm wastes have low quality, high hygroscopy, and low dimensional stability [11]. As such, they have not been widely used. However, there is an opportunity to develop oil palm wastes into usable material, for example, as a substitute for conventional boards, furniture, partitions, or acoustic materials, especially the parts of its trunk. The quality of oil palm trunk had been improved by thermal and chemical modification, impregnation, or the combination of the two in many previous studies [12–14]. In the impregnation method, the resin material is used to fill the cavities of the dry wood of the oil palm trunk such that its physical and mechanical properties can be improved. Phenol-formaldehyde resins are better impregnants than urea-formaldehyde resins, especially for conventional wood applications [13,14]. According to Deka and Saikia, the viscosity and specific gravity of resins affect the mechanical and dimension stability of woods. Their research has improved the stability dimensional and mechanical properties of *Anthocephalus Cadamba Miq* softwood [6]. Sain and Li studied the impregnation time and temperature of silane are able to enhance its strength properties [15]. The vacuum-pressure impregnation process applied to poplar sapwood achieved stronger waterproof properties [16]. Meanwhile, Qin et al. [17] found that the microstructure of eucalyptus and poplar is changing during the chemical impregnation process of wood.

Oil palm trunks also have the potential to be used as acoustic materials, such as absorbers, diffusers, and soundboards. Their application as a sound absorbent material has been supported by their natural properties, including their soft, porous, and fibrous structures. For acoustic applications, these properties need to be modified. The acoustic performance of wood, such as sound absorption coefficient and impedance acoustics are influenced by its moisture content, density, porosity, dimensional stability, mechanical resistance, and viscoelastic properties [18,19]. Density and mechanical resistance have a linear relationship with acoustic impedance. Further, the porosity is linearly propositional to the sound absorption coefficient of wood [18]. Moisture content caused a change in the fracture toughness of the wood to influence acoustic properties of wood [20]. Devallencourt et al. [21] had studied the viscoelastic properties of composite material cellulose in the variation of curing temperature and pH of MF. For MFFA/DMDHEU wood, an increase in temperature will decrease the storage modulus due to better chain mobility [22]. Same behaviour for *Catalpa bungei*, however, the storage modulus of heartwood had a 3°C lower glass transition temperature than sapwood due to lower lignin and higher extractives content [23].

In previous study, oil palm trunk had been modified by chemical modification to improve its physical properties. A two-step modification process followed this treatment. First, formalization modification was carried out with both pH 4 and pH 10, and second, impregnation modification was done using the MF resin. Research has shown that formalization in alkaline conditions improves the physical properties better than formalization in acidic condition [8]. In this study, the properties of oil palm trunk have also been improved using the same method, but the pressure of 5 bar at an hour was used during the impregnation process to expand their application. Applying pressure in the impregnation process and investigating the properties such as dimension stability, modulus of elasticity and dynamic-mechanical and acoustic properties is the novelty of this study. These results have also been confirmed by the morphological properties of the results from FTIR and SEM.

2 Experiment

2.1 Material Preparation

The samples of the oil palm trunk, over 30-years old, were from Banjarbaru of South Kalimantan, Indonesia. The samples were cut into pieces with a dimension of 15 cm × 5 cm × 1 cm, selected 1 m from the ground of the oil palm plant. All the samples were initially dried at 60°C for 24 h in order to prevent shrinkage and later dried at (103 ± 2)°C for 24 h to attain a moisture content of less than 10% [24]. The dried samples were stored at room temperature before the treatment. The average moisture content and density of the raw sample were 107.03% and 0.36 gr/cm^3, respectively. Materials to be used for the modification included formaldehyde solution, 37 wt% pH 4, NaOH 3 wt%, and MF resin supplied from commercial products [8].

2.2 Modification Process

The chemical modification of the oil palm trunk was performed in two steps. The first step constituted modification with a formaldehyde solution, known as the formalization process, to increase dimensional stability. The second was impregnation modification with MF resin under a pressure of 5 bar [14], in order to improve the physical, mechanical, dynamic-mechanical, and acoustic properties of the oil palm trunk. In the formalization process, the wood samples were immersed in formaldehyde solution under three conditions of pH 4, pH 6, and pH 10 for 5 days in sealed containers labeled as a_F, b_F, and c_F respectively. The degree of pH formalization was obtained by dropping the NaOH little by little into the formaldehyde solution to reach pH 6 and 10. Then, the structural changing of the oil palm trunk samples was observed by the FTIR spectra for all variation of pH conditions. Subsequently, the samples were dried in fume hood for a few days until the smell of formaldehyde disappeared or the mass of samples before and after the formalization process became almost the same. After the formalization, samples were impregnated by treating them with MF resin under a pressure of 5 bar at room temperature (32°C) for an hour for a complete modification. After this treatment, all the specimens were air-dried for a day before being cured at a temperature of 120°C for an hour for polymerization. Finally, the samples were dried in an oven at (103 ± 2)°C for 24 h to achieve a moisture content of <6% as acoustic material application [25]. Samples of oil palm trunk before and after modification are shown in Fig. 1, while their identities are listed in Tab. 1.

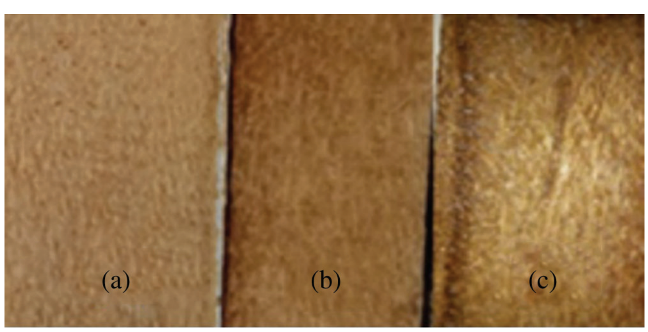


Figure 1: Samples of oil palm trunk (a) Raw (b) After formalization and (c) After complete modification

Table 1: The identified samples based on treatments

Samples	Treatments
R	Without treatment
N_F	Impregnation
a_F	Formalization at pH 4
b_F	Formalization at pH 6
c_F	Formalization at pH 10
a_{Fi}	Complete modification at pH 4
b_{Fi}	Complete modification at pH 6
c_{Fi}	Complete modification at pH 10

2.3 Characterization

2.3.1 Morphological Properties

A Scanning Electron Microscopy (SEM) instrument equipped with EDAX microanalysis data (EDAX-AMETEX model) used to investigate morphology and weight percent of chemical composition of oil palm trunks before and after modification. The sample matrix is made of resin, so SEM observation was conducted without gold coated on the sample's surface since the image resulted has been clear enough.

2.3.2 Infrared Spectral Analysis

Chemical compositions characterization of the oil palm trunk before and after modification was measured by Fourier Transform Infrared Spectroscopy (FTIR) using KBr pellet method from SHIMADZU. The data obtained in wave numbers range of 4000 cm^{-1} to 500 cm^{-1}.

2.3.3 Physical Properties

The moisture content of samples was calculated by using Eq. (1). Initial weight was measured, then dried at (103 ± 2)°C for 24 h to attain a moisture content of less than 10%.

$$MC(\%) = \frac{m_i - m_o}{m_o} x\ 100 \tag{1}$$

where, MC is the moisture content, m_i is the initial weight and m_o is the oven dry weight.

The sample were cut into 3 part with dimensions of 5 cm × 5 cm × 1 cm from the main sample. Then, the dimensions are measured with a caliper to calculate the accurate sample volume. The sample mass (m) was measured with analytical balance OHAUS with an accuracy of ± 0.1 g. The density of each sample was calculated using Eq. (2) as average density (ρ_s).

$$\rho_s = \frac{m}{V} \tag{2}$$

where ρ_s, m, and V are density (g/cm^3), mass and volume of the sample, respectively.

The porosity of samples and dimensional stability were measured refer to Samsudin et al. [26] and Dungani et al. [24] and the mechanical property of samples, modulus of elasticity (MOE), was measured by using Universal Testing Machine IBERTEST.

2.3.4 Dynamic Mechanical Analysis

Dynamic mechanical behavior of oil palm trunk before and after treatments were measured using a Dynamic Mechanical Analysis (DMA)/SDTA861e METTLER TOLEDO instrument in tensile mode refer to ASTM D 5026. Data analysis in the form of storage modulus (E') and damping factor (tan δ) behavior. Samples are cut to the size 2 cm × 0.2 cm × 0.3 cm, placed in the holder and then characterized as a frequency function with a test frequency range of 0.1 Hz to 50 Hz at a rate of 0.5 Hz, and temperature function with a test temperature range approximately 30°C to 125°C with the heating rate of 2 °C min^{-1} and oscillation responses at 1 Hz.

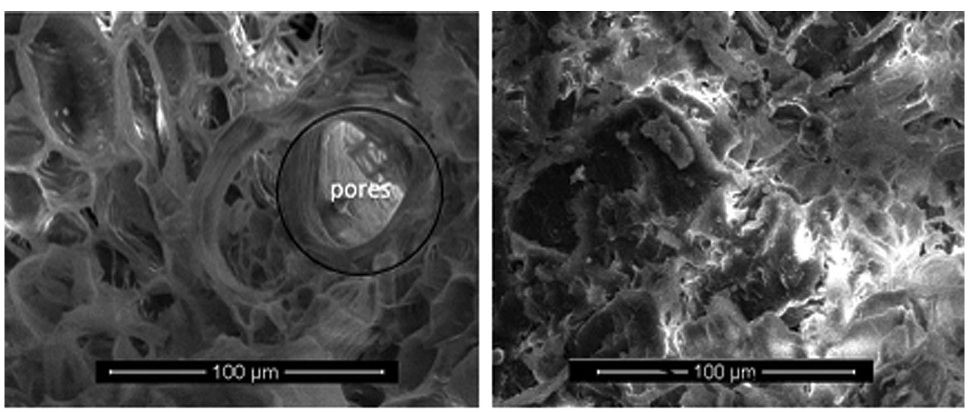
2.3.5 Acoustic Properties

The acoustic properties of samples such as sound absorption coefficient and impedance acoustics were measured using the Impedance Tube two microphones technique refer to ASTM E-1050, Brüel & Kjær 4206 type 03008. Samples were prepared with a diameter and thickness are 3 cm and 1 cm, respectively. Acoustics performance were measured in frequency ranges of 500 Hz to 6000 Hz.

3 Result and Discussion

3.1 Morphological Properties

The SEM images of oil palm trunk samples before and after formalization are shown in Fig. 2. As seen in Fig. 2a, the structure of the raw sample shows many pores and high roughness, whereas, after formalization, the structure of samples became more compact due to the effect of formaldehyde catalyzed by NaOH (Fig. 2b). This process yielded the crosslinking between polymer chains of the wood structure and CH_2O through a NaOH catalyst [4,8]. According to Hill, formaldehyde has the potential to react with two OH sites within the cell wall, resulting in cross-linking [4]. These cross-linkings protect the wood from fungus, such that the wood does not easily rot. The last reaction of this process was the evaporation of water molecules (H_2O) in the wood in order to reduce the hygroscopic properties of the wood. Decreasing moisture content increases the dimensional stability of wood [2,4].



(a) (b)

Figure 2: SEM oil palm trunk result (a) Raw and (b) After formalization

3.2 Infrared Spectral Analysis

The FTIR spectra of the oil palm trunk after formalization and impregnation modification are shown in Fig. 3. The oil palm trunk (raw samples, R) was dominated by peaks of functional group of 3422 cm^{-1} associated with O–H stretching vibrations in lignin, hemicellulose, and cellulose, as generally contained in cell-wall components [27]; 2905 cm^{-1} associated with C–H stretching vibrations in alkane groups; 1655 cm^{-1} associated with O–H bending vibration and water absorbed [28]; 1246 cm^{-1} associated with C–O stretching vibrations on carboxylic acid in hemicellulose; 1035 cm^{-1} associated with O–H stretching vibrations in cellulose and hemicellulose. After formalization (see Fig. 3, bottom), the intensity of absorption increased, and some peaks of functional groups shifted. It showed that the formalization treatments had created cross-links between the wood polymers and the formaldehyde. The highest peak was found in samples of a_F, followed by b_F and c_F, while the shifting of functional groups was shown in peaks 3422 cm^{-1}, 2905 cm^{-1}, and 1655 cm^{-1}.

FTIR spectra of the oil palm trunk samples after complete modification is shown in Fig. 3 (top part). The structure of the oil palm trunk appears to be dominated by methylene groups and amine groups. The peak of 3422 cm^{-1} (assigned in A), associated with the superposition of N–H stretching vibrations from secondary amines [29] and O–H bonds, shifted to a lower wavenumber. It indicated that the MF resin had penetrated the cavities and walls of the wood. The peak of 2905 cm^{-1} (assigned in B) had also shifted to a higher wavenumber. It indicated that the aldehyde group compositions in the wood cell had bonded with the MF resin polymer chains. The carbonyl group in 1730 cm^{-1} associated with lignin and hemicellulose [27,30] (assigned in C) disappeared due to the presence of MF resin. The peak of 1655 cm^{-1} (assigned at D) also disappeared due to polymerization, but two new functional groups of 1512 cm^{-1} and 1460 cm^{-1}, associated with C=C stretching the aromatic ring of the lignin ring, had emerged. New peaks also appeared in 1551 cm^{-1}, 1549 cm^{-1}, 1553 cm^{-1}, and 1549 cm^{-1} for a_{Fi}, b_{Fi}, $c_{Fi,}$ and d_{Fi}, respectively. It related to the stretching of the vibration ring of C–H methylene and C–N [29]. The peak band of 1377 cm^{-1} (assigned in E), associated with the vibration of the methylene bending C–H and polysaccharide deformation [31], had expanded after modification. It showed that the MF resin had penetrated the wood pores and cell walls. Besides, the peaks of 1246 cm^{-1} (assigned in F) and 1053 cm^{-1} (assigned in G) had shifted to smaller wave-numbers associated with the stretching absorption of C–N aliphatic amines and C–O. The important peaks after modification were revealed by the emergence of the new functional group at 812 cm^{-1} (assigned in H) for all the samples. It was associated with the characteristic of the fingerprint absorption region of MF, called vibration triazine ring [9,29]. Higher absorbance peaks indicated that the MF resin had been absorbed more [9]. Based on FTIR spectra trends, the pH 10 (c_{Fi}) treatment appears to have protected the cell walls of wood samples better than other treatments, in accordance with Hill [4]. Therefore, it can be concluded that increasing pH modification strengthened the cross-linking between wood polymers.

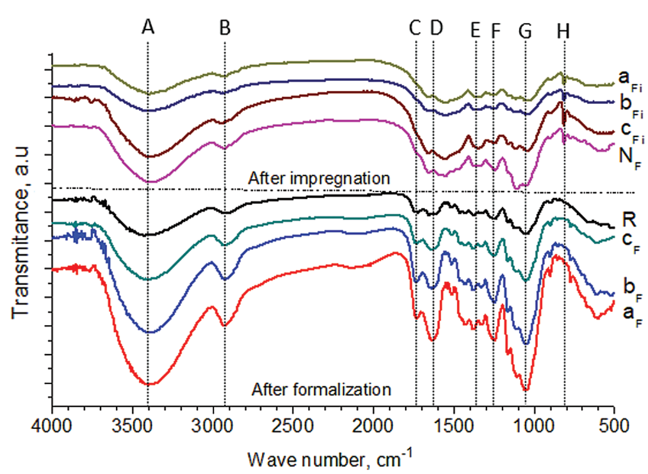


Figure 3: FTIR spectra of oil palm trunk for raw sample (R), after formalization (bottom) and impregnation (top) by varying pH formalization

Impregnation of MF resin into palm oil trunk samples have successfully penetrated pore cavities and coated cell walls of wood, as shown in Fig. 4 (compared to Fig. 2). The N_F image shows that the samples still had cavities, while the a_{Fi} image shows that the MF resin had covered the pores on the cell wall of the wood; however, the surfaces still had some granularity and roughness caused by the O–H bonding between formaldehyde solution and polymer chain of wood, which had not been strong in acid condition. The image of b_{Fi} and c_{Fi} shows that the interaction between the MF resin and cell wall of the wood had a strong bonding under the effect of NaOH as a catalyst. The catalyst reduced waxy substances and O–H content in wood structures such that the crosslink between the MF resin and the wood-polymer became stronger.

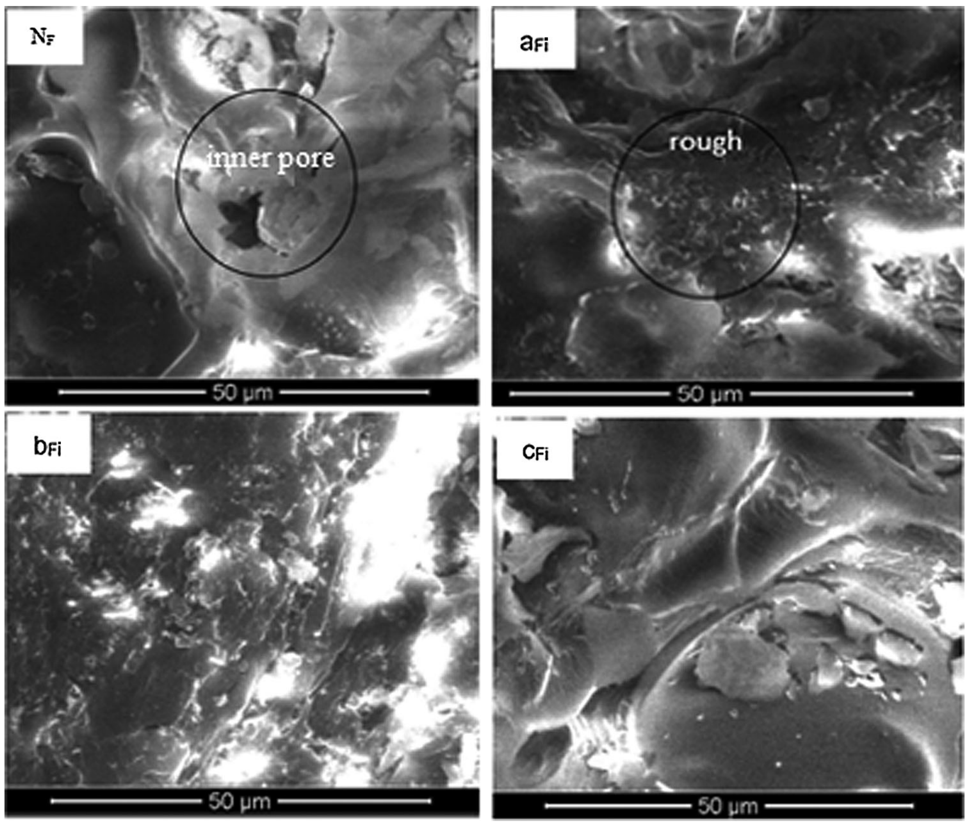


Figure 4: SEM image of oil palm trunk after complete modification

Tab. 2 explains the oil palm trunk chemical compositions before and after modification based on the EDAX results. Formalization reduced C and O content (assigned R_F) in raw samples due to reaction among chemical constituent of raw sample and CH_2O by catalyst NaOH. It was indicated that this modification created the crosslinks between O and C in wood. After impregnation, the MF resin had penetrated the pores and cavities of the wood. O and C had bound with N, which is evident by the fact that there is N (wt%) in EDAX data. This is confirmed by the FTIR spectra seen in Fig. 3.

3.3 Physical Properties

The presence of N element enhanced the physical and mechanical properties of the samples, as shown in Tab. 3. The impregnation modifying decreased moisture content up to 6%, in accordance with Göken [25]. According to Tab. 3, the modification increased the density and the modulus of elasticity and decreased the porosity and the coefficient of volume swelling after treatment. These results are in alignment with the findings of previous research studies [5,6]. The highest modulus of elasticity of the oil palm trunk was found in the sample without formalization (N_F). However, the best stability of dimensions was found in the sample treated with pH 10 (c_{Fi}). We found that after impregnation with MF, the O–H content in wood is reduced due to part of the H bonds bind the compounds in MF resin to form amine compounds (NH) at wave number 3422 cm^{-1}. Moreover, the functional group at wave number 1655 cm^{-1} which is O–H compounds have been replaced by C–N and C–H compounds. This is one of our reason, that formalization in an alkaline setting has reduced O–H compounds more than any other treatment. This impact the dimensional stability of wood against humidity in environmental conditions (see Fig. 3).

Table 2: Oil palm trunk compositions based on EDAX results

Element	Oil palm trunk content (wt%)					
	R	R_F	a_{Fi}	b_{Fi}	c_{Fi}	N_F
C	42.50	42.15	32.89	34.42	32.52	34.13
O	54.71	43.89	28.89	38.22	36.13	35.80
N			35.36	25.26	29.67	27.39
Na, Cl, K, Si, Al, Ca, S	3.09	13.98	2.87	2.11	1.69	2.68

Table 3: Physical properties of oil palm trunk

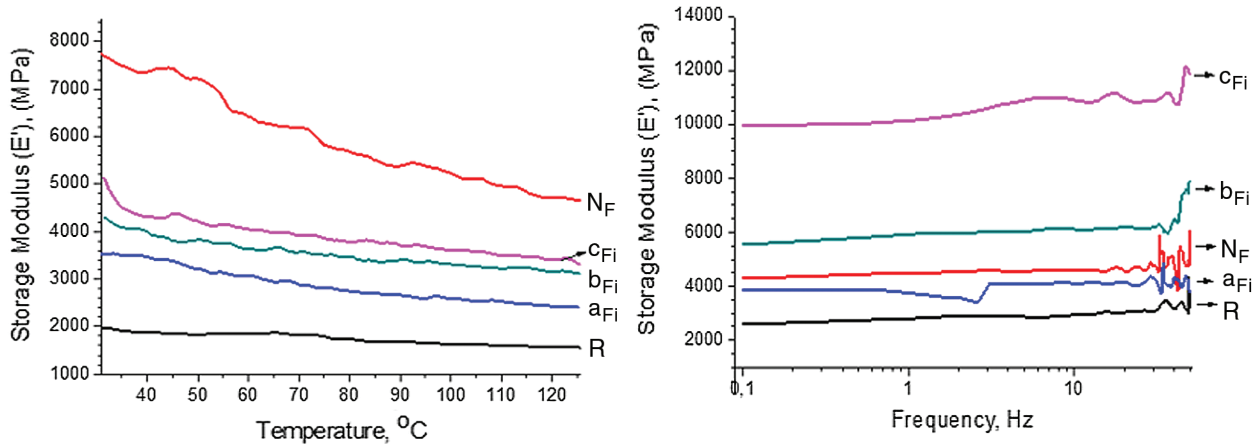
Physics properties	Impregnation by MF				
	R	a_{Fi}	b_{Fi}	N_F	c_{Fi}
Density (gr/cm^3)	0.36	0.74	0.72	0.73	0.76
Porosity (%)	51.50	17.43	16.01	13.72	16.25
Swelling (%)	4.49	3.20	3.40	1.74	0.72
MOE (M.Pa)	916.23	1603.29	1777.41	3078.05	2460.42

3.4 Dynamic Mechanical Analysis

3.4.1 Storage Modulus

Chemical modification treatment also changed the dynamic-mechanical properties of the oil palm trunk samples. Fig. 5 shows the effect of variations in formalization conditions on storage modulus (E′) as a function of temperature (a) and frequency (b) after complete modification. The storage modulus increased after modification of lower temperature and decreased with an increase in temperature (Fig. 5a). It was influenced by the bending and stretching movements of molecules in the wood samples [32]. These results are in alignment with the findings of Devallencourt et al. [21], which suggested that the storage modulus of cellulose modified by MF from low temperatures to 120°C decreased and was only influenced by bending and stretching movement. A higher E' indicates a higher stiffness and load-bearing ability of woods [32,33]. The storage modulus of N_F was higher than that of c_{Fi}, b_{Fi}, $a_{Fi,}$ and raw samples (R). It was according to the MOE presented in Tab. 3. However, decreasing of the graph (N_F) was not as smooth as others due to the presence of lignin, which caused the interface adhesion between the cell wall of the wood and the MF resin to have less binding. After curing, MF became hard and grainy and still retained some pores. Increasing the temperature tends to enhance the movement of particles in wood.

Thus, molecules on the wood structures would move irregularly when the signal wave from the DMA instrument forced woods with increasing temperature of measurement. In contrast to other samples, the trend was seen to be smoother. It was because some lignin content had been removed from the cell wall of the wood during the formalization process. This modification caused a better interface adhesion between the cell wall of the wood and the MF resin [30].



(a) (b)

Figure 5: Storage modulus (E') from oil palm trunk as function of (a) Temperature and (b) Frequency

Fig. 5b shows the storage modulus for all samples as a function of frequency. The storage modulus slowly increased according to frequency. Resonance peaks emerged in wood samples of a_{Fi} and N_F after the chemical modification treatment. These resonance peaks were generated due to the cavities and pores existing in the wood. Lesser number of resonance peaks indicated higher elasticity and higher load-bearing capability. Peaks of resonance frequency indicated the presence of vibrational energies at the same frequency such that the sound energy could reach the wall faster. Fig. 5b shows that the modification by b_{Fi} and c_{Fi} had better ability to increase the storage modulus and to remove resonance peaks in samples. The N_F samples had resonance peaks at the frequency of 32.6 Hz and a harmonic peak of 42.1 Hz. This indicated that the samples still had many pores after the treatment, as the wood structure had not been damaged before it was impregnated. By modification in a_{Fi}, resonance had been generated at frequencies below 10 Hz and 35 Hz. It was in accordance with Hill, who showed that formaldehyde did not bond with wood's elements under acidic conditions without a catalyst [4]. Increasing of formalization pH can eliminate resonance from wood. It further showed that higher pH conditions can lead to better absorption of the MF resin into the wood structure. Menard et al. [32] said that these peaks of resonance unfavorably affect the wood performance on the application, as the system tends to become unstable. Lesser number of resonant peaks indicated that the wood had become tougher and harder.

3.4.2 Damping Factor

Damping factor (tan [δ]) of oil palm trunk samples before and after modification as functions of temperature and frequency are presented in Fig. 6. The damping factor is related to the degree of molecular mobility in the polymeric material [33]. This parameter plays an important role in determining the performance of wood samples as acoustic materials, which are shown by their ability to absorb sound energy. The wood sample absorbed more energy when the value of the damping factor was greater than 1 [25]. This contradicted the modified samples in this study that attained less than 0.05 after modification in the temperature range of 60°C to 120°C due to the samples being denser and harder. Fig. 6a explains that the raw sample trends had the highest value of damping factor in the range 50°C–82°C. The damping factor of other samples tended to be stable after temperature 60°C, caused by faster mobility of molecules and regular movement. At lower temperatures, however, the intermolecular space volume in the wood was large, so the molecules moved more slowly.

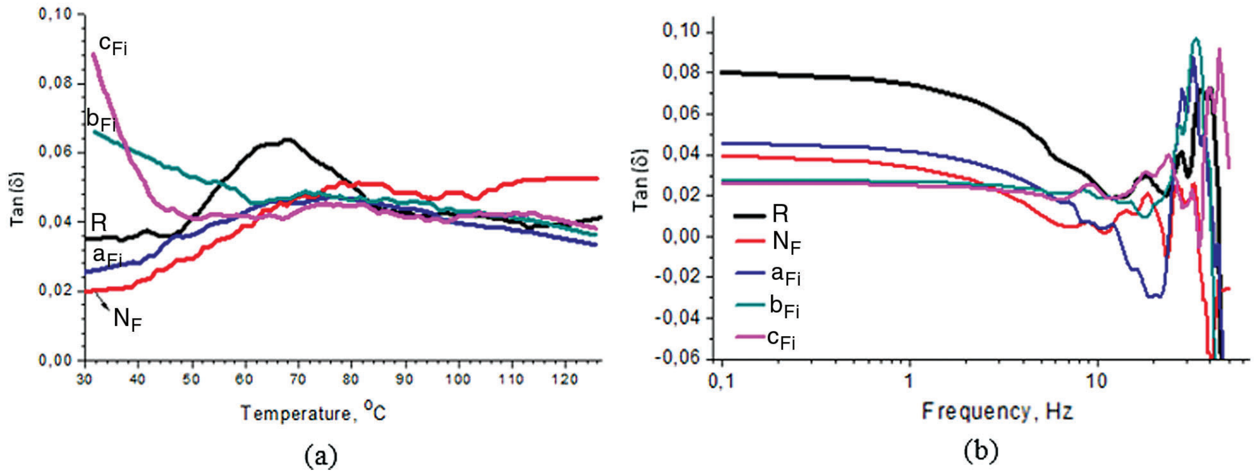


Figure 6: Tan (δ) of oil palm trunk as function of (a) Temperature and (b) Frequency

Fig. 6b shows the trend of the samples before and after the modification as a frequency function. The damping factor decreased by increasing frequency after the treatment. It indicated that the MF resin had filled and coated the cell wall of the wood. The trend of tan δ in the sample b_{Fi} and c_{Fi} was most stable in frequencies lower than 10 Hz due to the strong binding between the structure of wood and the MF resin, such that the molecular mobility of wood was also reduced. This indicated that the wood had become more rigid and hard. The trend of tan δ oscillated in frequency above 10 Hz due to the presence of air in the pores of the wood structures. In this study, the damping factor both in the function of temperature and varied frequency was obtained in the range of 0.1 to 0.02. This value is in alignment with the results of Göken et al. [25], which found the range from about $0.06 < \tan \delta < 0.1$ for new and old spruce wood at a moisture content of nearly 8% and Weigst [34], which got between 0.1 and 0.002 for air-dry wood at room temperature, making it useful for acoustic application.

3.4.3 Acoustic Properties

The formalization treatment led the pores to shrink and the wood fibres to dry, making them easier to separate. It was caused by the reduction of the waxy substance in wood during the formalization process. After impregnation by the MF resin, the wood became denser, so the porosity of the wood reduced. Wood stiffness increased, and wood elasticity reduced. This effect was aligned with Gilani et al. who mentioned that the waxy component (lignin) could influence the viscoelastic properties of wood [1]. The number of pores affects the movement of sound particles in the wood [35], and so, the sound absorption properties (α) decrease if the number of pores in the wood is less. Fig. 7 represented specimen test samples. In Fig. 8, it is seen that the peak of sound absorption coefficient of samples N_F shifted from 2784 Hz to 1816 Hz for c_{Fi}, to 2704 Hz for a_{Fi}, and 2990 Hz for b_{Fi}, while the sound absorption coefficient without formalization of $\alpha = 0.58$ reduced to $\alpha = 0.54$ for b_{Fi}, to $\alpha = 0.46$ for a_{Fi}, and $\alpha = 0.36$ for c_{Fi} (the lowest). It proved that absorption properties were influenced by the number of inner pores. This was confirmed by the SEM images shown in Fig. 4. Kendronne has investigated the sound absorption coefficient from the oil palm trunk by varying the resonator geometry on the surface of the wood panel. For the frequency of 2000 Hz with the sample thick is 1.2 cm, diameter, and depth of an orifice of 5 mm and 10 mm, respectively, obtained α = 0.38 is higher than the sample of this study [36]. It proved that variations in chemical treatments have an impact on the variation in the fraction and inner pore dimensions. This accumulatively affects the viscoelastic properties of the studied material, especially also to its impedance and resonance response. These are shown in Figs. 8 and 9 in the form of a peak shift in its sound absorption coefficient and impedance ratio.

Figure 7: Specimen samples for acoustics test: pH 4, pH 6 and pH 10

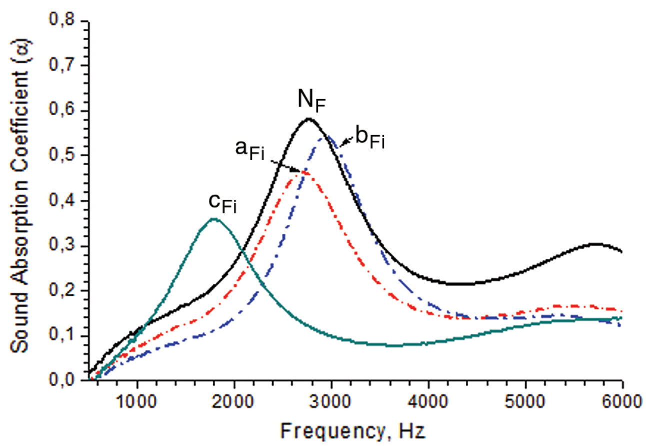


Figure 8: The sound absorption coefficient of oil palm trunk samples after modification

Fig. 9 shows the trend of acoustic impedance samples after treatment. Acoustic impedance is the ability of materials to transmit acoustic signals. The real part (r) (Fig. 9a) represents sound transmission that passes the material of wood, while the imaginary part (i) (Fig. 9b) represents the released dissipation energy while moving particles in the wood. The trend in the graph shows that the sample treated with pH 10 (assigned in c_{Fi}) had the lowest sound signal transmission. It indicated that the c_{Fi} sample had lower sound absorption ability and dissipation energy than others. The trend seems unique, where the acoustic impedance (r) bandwidth became wider at frequencies of 1500–2500 Hz. This characteristic showed that the modification made in this study expanded the acoustics performance of the oil palm trunk.

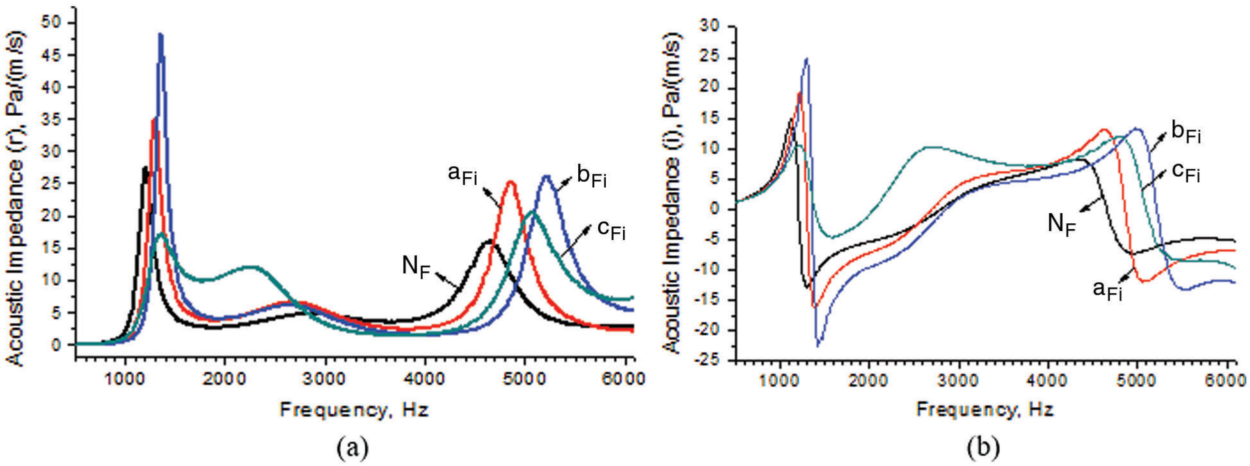


Figure 9: The acoustic impedance of oil palm trunk samples after treatment. (a) Real part and (b) Imaginary part

4 Conclusion

The improvement of physical, dynamic-mechanical, and acoustic properties was carried out by changing the structure of oil palm trunk through a two-step chemical modification process. First, the formalization modification changed the structure of the natural properties to make the wood denser and drier and cause shrinkage of pores. Then, the impregnation modification, followed by the pressure treatment, enhanced the physical, mechanical, and dynamic mechanism of the raw oil palm trunk. The combination of both the steps affected the acoustic properties of the oil palm trunk. Modification by pH 10 had the lowest sound absorption coefficient and the widest impedance acoustic frequency bandwidth, with the lowest dimension stability. Based on these results, it can be concluded that the method employed in this study managed to enhance the oil palm trunk waste performance.

Funding Statement: The authors would like to acknowledge the Beasiswa Pendidikan Pascasarjana Dalam Negeri (BPPDN) KEMDIKBUD Indonesia who provided doctoral scholarship.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

References

1. Gilani, M. S., Pflaum, J., Hartmann, S., Kaufmann, R., Baumgartner, M. et al. (2016). Relationship of vibro-mechanical properties and microstructure of wood and varnish interface in string instruments. *Journal of Applied Physics, A,* 259–260.
2. Chieng, B. W., Lee, S. H., Ibrahim, N. A., Then, Y. Y., Loo, Y. (2017). Isolation and characterization of cellulose nanocrystals from oil palm mesocarp fiber. *Journal of Polymers, 9(12),* 355. DOI 10.3390/polym9080355.
3. Malutan, T., Nicu, R., Popa, V. I. (2008). Contribution to the study of hydroxymetylation reaction of alkali lignin. *BioResources, 3,* 13–20.
4. Hill, C. A. S. (2006). *Wood modification-chemical, thermal and other processes*. Chapter 4, pp. 93. Hoboken, NJ: John Wiley & Son.
5. Altun, S. (2017). Effects of chemical modification on wood properties. *Online Journal of Science and Technology, 7,* 75–81.
6. Deka, M., Saikia, C. N. (2000). Chemical modification of wood with thermosetting resin: effect on dimensional stability and strength property. *Bioresource Technology, 73(2),* 179–181. DOI 10.1016/S0960-8524(99)00167-4.
7. Gindl, W., Zargar-Yaghubi, F., Wimmer, R. (2003). Impregnation of softwood cell walls with melamine-formaldehyde resin. *Bioresource Technology, 87(3),* 325–330. DOI 10.1016/S0960-8524(02)00233-X.

8. Manik, T. N., Mashuri, M., Darminto, D. (2019). Study on formalization of oil palm trunk modified by melamine formaldehyd. *Materials Science Forum, 966,* 151–156. DOI 10.4028/www.scientific.net/MSF.966.151.
9. Gindl, W., Hansmann, C., Gierlinger, N., Schwanninger, M., Hinterstoisser, B. et al. (2004). Using a water-soluble melamine-formaldehyde resin to improve the hardness of norway spruce wood. *Journal of Applied Polymer Science, 93(4),* 1900–1907. DOI 10.1002/app.20653.
10. Ormondroyd, G. A. (2015). Woodhead publishing series in composites science and engineering. In: Ansell, M.P. (ed.), *Handbook of wood composites; Adhesives for wood composites,* vol. 3, pp. 52–53. Amsterdam, Netherlands: Elsevier.
11. Lamaming, J., Hashim, R., Leh, C. P., Sulaiman, O., Sugimoto, T. et al. (2015). Isolation and characterization of cellulose nanocrystals from parenchyma and vascular bundle of oil palm trunk (Elaeis guineensis). *Carbohydrate Polymers, 134(2),* 534–540. DOI 10.1016/j.carbpol.2015.08.017.
12. Khalil, H. P. S. A., Abdullah, C. K., Jawaid, M., Issam, A. M. (2012). Physical and thermal properties of microwave-dried wood lumber impregnated with phenol formaldehyde resin. *Journal of Composite Materials, 47(28),* 3565–3571. DOI 10.1177/0021998312467386.
13. Salim, N., Hashim, R., Sulaiman, O., Ibrahim, M., Nasir, M. et al. (2016). Improved performance of compressed oil palm trunk prepared from modified pre-steaming technique. *Journal of the Indian Academy of Wood Science, 13(1),* 1–7. DOI 10.1007/s13196-015-0155-1.
14. Dungani, R., Jawaid, M., Khalil, H. P. S. A., Jasni, J., Aprilia, S. et al. (2013). A review on quality enhancement of oil palm trunk waste by resin impregnation: Future material. *BioResources, 8(2),* 3136–3156.
15. Sain, M., Li, H. (2002). Enhancement of strength properties of mechanical pulps. *Journal of Wood Chemistry and Technology, 22(4),* 187–197. DOI 10.1081/WCT-120016257.
16. Wei, X., Tao, D., Sheng, X., Zhang, M. (2018). Modification of poplar wood using polyhexahydrotriazine and its effect on hygroscopicity. *Journal of Wood Chemistry and Technology, 38(3),* 214–223. DOI 10.1080/02773813.2018.1432654.
17. Qin, Y., Dong, Y., Li, J. (2019). Effect of modification with melamine-urea-formaldehyde resin on the properties of eucalyptus and poplar. *Journal of Wood Chemistry and Technology, 39(5),* 360–371. DOI 10.1080/02773813.2019.1636821.
18. Smardzewski, J., Batko, W., Kamisiński, T., Flach, A., Pilch, A. et al. (2014). Experimental study of wood acoustic absorption characteristics. *Holzforschung, 68(4),* 467–476. DOI 10.1515/hf-2013-0160.
19. Brémaud, I. (2012). Acoustical properties of wood in string instruments soundboards and tuned idiophones: biological and cultural diversity. *Journal of the Acoustical Society of America, 131(1),* 807–818. DOI 10.1121/1.3651233.
20. Li, X., Li, M., Ju, S. (2020). Frequency domain identification of acoustic emission events of wood fracture and variable moisture content. *Forest Products Journal, 70(1),* 107–114.
21. Devallencourt, C., Saiter, J. M., Capitaine, D. (2000). Reactions between melamine formaldehyde resin and cellulose: Influence of pH. *Journal of Applied Polymer Science, 78,* 1884–1896. DOI 10.1002/1097-4628(20001209)78:11<1884::AID-APP60>3.0.CO;2-2.
22. Hazarika, A., Mandal, M., Maji, T. K. (2014). Dynamic mechanical analysis, biodegradability and thermal stability of wood polymer nanocomposites. *Composites Part B: Engineering, 60,* 568–576. DOI 10.1016/j.compositesb.2013.12.046.
23. Li, Z., Lu, J., Cao, J., Jiang, J. (2020). Comparative study of the hydrothermal softening characteristics of heartwood and sapwood. *Forest Products Journal, 70(3),* 243–248.
24. Dungani, R., Khalil, A. H. P. S., Islam, M. N., Sumardi, I., Aditiawati, P. et al. (2016). Soil burial degradation of oil palm shell (OPS) nanofiller and phenol formaldehyde (PF) resin-impregnated oil palm trunk lumber (OPTL): Dimensional stability and mechanical properties. *Journal of Biobased Materials and Bioenergy, 10,* 1–7. DOI 10.1166/jbmb.2016.1585.
25. Göken, J., Fayed, S., Schäfera, H., Enzenauer, J. (2018). A study on the correlation between wood moisture and the damping behaviour of the tonewood Spruce. *Acta Physica Polonica A, 133,* 1241–1260. DOI 10.12693/APhysPolA.133.1241.

26. Samsudin, E. M., Ismail, L. H., Kadir, A. A., Nasidi, I. N. (2017). Thickness, density and porosity relationship towards sound absorption performance of mixed palm oil fibers. *Proceedings of the 24th International Congress on Sound and Vibration,* pp. 23–27. London.
27. Horikawa, Y., Hirano, S., Mihashi, A., Kobayashi, Y., Zhai, S. et al. (2019). Prediction of lignin contents from infrared spectroscopy: Chemical digestion and lignin/biomass ratios of cryptomeria japonica. *Applied Biochemistry and Biotechnology, 188(4),* 1066–1076.
28. Abraham, E., Deepaa, B., Pothan, L. A., Jacob, M., Thomas, S. et al. (2011). Extraction of nanocellulose fibrils from lignocellulosic fibres: A novel approach. *Carbohydrate Polymer, 86,* 1468–1475. DOI 10.1016/j.carbpol.2011.06.034.
29. Merline, D. J., Vukusic, S., Abdala, A. A. (2013). Melamine formaldehyde: curing studies and reaction mechanism. *Polymer Journal, 45(4),* 413–419. DOI 10.1038/pj.2012.162.
30. Jayamani, E., Hamdan, S., Heng, S. K., Rahman, M. R., Bakri, M. K. B. (2016). Acoustical, thermal, and morphological properties of zein reinforced oil palm empty fruit bunch fiber bio-composites. *Journal of Applied Polymer Science, 44164,* 1–8.
31. Herrera, R., Krystofiak, T., Labidi, J., Liano-Ponte, R. (2016). Characterization of thermally modified wood at different industrial conditions. *Drewno, 59,* 151–164.
32. Menard, K. P., Menard, N. (2017), *Encyclopedia of analytical chemistry; Dynamic mechanical analysis,* pp. 5–6. Hoboken, NJ: John Wiley & Son, Ltd.
33. Joseph, S., Appukuttan, S. P., Kenny, J. M., Puglia, D., Thomas, S. et al. (2010). Dynamic mechanical properties of oil palm microfibril-reinforced natural rubber composites. *Journal of Applied Polymer Science, 117,* 1298–1308.
34. Wegst, U. G. K. (2006). Wood for sound. *American Journal of Botany, 93(10),* 1439–1448. DOI 10.3732/ajb.93.10.1439.
35. Maderuelo-Sanz, R., Morillas, J. M. B., Castizoa, M., Escobar, V. G., Gozalo, G. R. (2013). Acoustical performance of porous absorber made from recycled rubber and polyurethane resin. *Latin American Journal of Solids and Structures, 10(3),* 585– 600. DOI 10.1590/S1679-78252013000300008.
36. Kerdtongmee, P., Saleh, A., Eadkhong, T., Danworaphong, S. (2016). Investigating sound absorption of oil palm trunk panels using one-microphone impedance tube. *BioResources, 11(4),* 8409–8418. DOI 10.15376/biores.11.4.8409-8418.