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Full Length Research Article

Modification of Fast-Growing Wood into Magnetic Wood with Impregnation Method Using Fe_3O_4 Nanoparticles

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ABSTRACT

Fast-growing wood is rarely used by the community because of its low quality. This study aimed to modify the sengon (*Falcataria moluccana*) and jabon (*Anthocephalus cadamba*) into magnetic wood so they have new functions. In this study, the modification process was performed by impregnating five-level concentrations of Fe_3O_4 nanoparticles dissolved in two different dispersants, namely water and a mixture of furfuryl alcohol and water. The impregnation process is initiated by a vacuum of -0.5 bar, followed by a pressure of 1 bar for 120 min. The addition of furfuryl alcohol to the impregnation solution significantly increased the physical properties of magnetic wood. The presence of Fe_3O_4 in wood is also proven by the Fe-O groups observed from the FTIR spectrum analysis. The magnetic field strength also increased as the concentration level of Fe_3O_4 increased. Based on the results of this research, the best treatment was obtained on magnetic wood of sengon and jabon with furfuryl alcohol and Fe_3O_4 nanoparticles concentration of 7.5%.

1. Introduction

Fast-growing wood species are known to have low quality, making them less popular in the wood industry. The high content of juvenile wood causes fast-growing wood to have a low density and durability (Rahayu et al. 2014). Fast-growing woods such as sengon (*Falcataria moluccana*) and jabon (*Anthocephalus cadamba*) woods are currently only used as insulating boards, plywood, carpentry wood, and crates (Anggraini et al. 2021). Many studies have been conducted to modify the wood using the impregnation process to improve its quality. Several recent studies reported the improvement of the physical properties of sengon and jabon wood through the impregnation process using nanoparticles (Dirna et al. 2020; Prihatini et al. 2020a; Rahayu et al. 2020; Rahayu et al. 2022a). The nanometer-sized particles can be well distributed and penetrate the wood because of their low viscosity, high dispersion stability, and effectiveness in coating wood surfaces (Fufa and Hovde 2010; Teng et al. 2018). Thus, modified fast-growing wood can also be used as raw material for construction and furniture. However, apart from what has been mentioned in previous studies, the function of fast-growing wood is still limited. Therefore, this research focuses on creating a new function for fast-growing wood, namely magnetic wood with good physical properties.

Magnetic wood is a multifunctional wood that has several advantages. It can be used as a heat conductor because the presence of Fe_3O_4 nanoparticles can increase the thermal conductivity of wood. In addition, magnetic wood can absorb electromagnetic wave radiation emitted by mobile phones, Local Area Networks (LAN), and other household appliances to reduce health risks to radar wave radiation (Oka et al. 2012). Wood can be magnetized by the in-situ and ex-situ processes. Dong et al. (2016) and Rahayu et al. (2022b) succeeded in synthesizing magnetic wood using in situ process through the chemical coprecipitation method. On the other hand, Oka and Fujita (1999) also succeeded in synthesizing magnetic wood through impregnation, coating, and mixing the powder or magnetic fluid with sawdust, then making boards.

In this study, magnetic wood was synthesized by the impregnation process of Fe_3O_4 nanoparticles. The Fe_3O_4 nanoparticles were used because of their advantages, such as increasing the dimensional stability of wood and having magnetic properties which can absorb electromagnetic waves and attract or be attracted by magnets (Ayrilmis and Kaymakci 2013; Trey et al. 2014). Besides that, Fe_3O_4 nanoparticles are widely available in marketplaces (Tang and Fu 2020). However, the Fe_3O_4 nanoparticles are insoluble in pure water, causing the wood impregnation process ineffective (Schwertmann et al. 2003; Wahyuningtyas et al. 2022). Therefore, furfuryl alcohol (FA) was used in this research as a dispersant of Fe_3O_4 nanoparticles to penetrate deeper into the wood.

Furfuryl alcohol (FA) used in this research is an environmentally friendly chemical made from hemicellulose derived from agricultural waste. FA has the fire retardant characteristic, leaching resistance, and can be used as a sealant because of its outstanding resistance from corrosive chemicals when cross-linked to stabilize the wood dimension (Iroegbu and Hlangothi 2019; Lin et al. 2022). In addition, FA is suitable to be applied to wood with open pits, so it can fill the cell walls and make the wood denser (Teng et al. 2018). The use of FA in magnetic wood synthesis has been reported by Dong et al. (2016) and has succeeded in increasing the impregnation ability of Fe_3O_4 nanoparticles by *in situ* process. Furthermore, Wahyuningtyas et al. (2022) studied *ex-situ* impregnation using Fe_3O_4 nanoparticles mixed with FA as an impregnation solution. They reported that FA could disperse Fe_3O_4 into smaller sizes, so it penetrated the wood and significantly improved its magnetic and physical properties. Therefore, in this study, the magnetic wood was synthesized by an ex-situ impregnation process of Fe_3O_4 nanoparticles and a mixture of Fe_3O_4 nanoparticles with FA to obtain the optimum method and concentration.

2. Materials and Methods

2.1. Materials

The materials used in this study were 5 years of sengon wood (*Falcataria moluccana*) and jabon wood (*Anthocephalus cadamba*) from a community forest in Bogor, West Java, Indonesia. Sengon wood has a branch-free height of 9 m and a diameter of 43 cm, and jabon wood has a branch-free height of 7 m and a diameter of 28 cm. The chemicals used are furfuryl alcohol (Sigma Aldrich Pte. Ltd., China), Fe_3O_4 nanoparticles (Nanjing Aocheng Chemical Co., China, 15 ± 5 nm), and demineralized water.

2.2. Methods

2.2.1. Sample preparation

Sengon and jabon woods were cut 50 cm from the base to the branch-free height, then made as a board. All samples were obtained from the same tree with processing simultaneously, thereby reducing variability. Wood samples were cut without distinguishing between sapwood and heartwood, using a chainsaw and circular table saw. The samples were cut in size 2 cm × 2 cm × 2 cm following BS-373:1957 for 100 samples in each wood (10 samples for each treatment).

2.2.2. Preparation of impregnation solution

Two types of solutions prepared in this study were aqueous and mixed dispersant (demineralized water:FA, mole ratio 1:1), each containing Fe_3O_4 nanoparticles in five level concentrations (w/v; 0.5%, 1.5%, 2.5%, 5%, and 7.5%). The aqueous and mixed dispersants solutions were mixed using a magnetic stirrer (IKA C-MAG HS 7, China) for 15 min, then mixed using a sonicator (CGOLDENWALL, China) with an amplitude of 40% for 30 min.

2.2.3. Impregnation process

The impregnation process was adapted from previous studies (Dong et al. 2016; Oka and Fujita 1999; Rahayu et al. 2020). First, the samples were immersed with the solutions in the impregnation tube under a vacuum of -0.5 bar for 120 min, followed by a pressure of 1 bar for 120 min. The impregnated samples were then wrapped in aluminum foil and placed in an oven at 65°C for 12 h for polymerization. After that, the aluminum foil was removed, and the samples were dried at 103 ± 2°C. The impregnation tube used in this research is shown in **Fig. 1**.

Fig. 1. The impregnation tube used in this study.

2.2.4. Wood physical properties test

The physical properties test of wood includes weight percent gain (WPG), density, and bulking effect (BE) was calculated by the following formulas:

$$WPG\ (\%) = \frac{W_1 - W_0}{W_0} x\ 100 \quad (1)$$

$$\rho\ (g.cm^{-3}) = \frac{W_1}{V_1} \quad (2)$$

$$BE\ (\%) = \frac{V_1 - V_0}{V_0} x\ 100 \quad (3)$$

where W_0 is the dry weight before impregnation, W_1 is the dry weight after impregnation, V_0 is the dry volume before impregnation, and V_1 is the dry volume after impregnation.

2.2.5. FT-IR analysis

The chemical composition of the magnetic wood was analyzed using FT-IR (Fourier Transform Infra-Red Spectroscopy) (Thermo Scientific, Nicolet 6700, Waltham, United States), with a wavenumber of 4000 to 400 cm^{-1} for 32 scans. Impregnated wood samples were ground to a particle size of 200 mesh and embedded in potassium bromide (KBr) pellets with a ratio of 1:100.

2.2.6. Characteristics of magnetic properties

The characteristic of magnetic properties was analyzed using Magnetometer, the smartphone software used to measure the magnetic field strength of the magnetic wood (Indrasari 2012; Septianto et al. 2017). The smartphone used in this study was Android 10 (Vivo Y30 1938, Indonesia). The software used was Magnetometer version 1.1 (SpaceRocket, EU). Magnetic field measurements were carried out at a distance of 2 cm from the wood. Before starting the test, the software is calibrated according to the instructions.

2.2.7. Data analysis

This study used a completely randomized design and was evaluated using ANOVA, followed by Duncan's test at $\alpha = 1\%$. Data analysis used the SPSS (Statistical Package for Service Solution, from IBM, United States) version 25.0 program.

3. Results and Discussion

3.1. The Physical Properties of Magnetic Wood

Weight percent gain (WPG) is the percentage of the weight increase of the wood after the impregnation process. The WPG of the magnetic wood (MW) and magnetic wood with FA-dispersant addition (MWD) are shown in **Fig. 2**. The highest WPG of MW sengon was obtained at a concentration of 7.5% (79.90%), whereas in the treatment of WM jabon, it was obtained at 5% (2.55%). On the other hand, the concentration of 7.5% in WMD sengon (78.90%) and jabon (56.89%) reached the highest WPG after the impregnation process.

The lower WPG of the MW sample was due to the Fe_3O_4 nanoparticles could not be dissolved with demineralized water, causing the solutions to form two phases, solid and liquid (**Fig. 3a**). This caused the water could not bring Fe_3O_4 nanoparticles to penetrate the cell wall through the holes on the wood surfaces. Furthermore, the study of Wahyuningtyas et al. (2022) showed that Fe_3O_4 nanoparticles dispersed with FA deposited in the wood cell wall with an average particle size of below 50 nm, which is smaller than Fe_3O_4 nanoparticles dispersed with water because FA can solvate Fe_3O_4 well (Li et al. 2020). Theerdhala et al. (2010) and Masoudi et al. (2012) stated that Fe_3O_4 nanoparticles have an unstable characteristic that can make the particle easy to agglomerate and oxidize. The agglomeration process properties occur due to the magnetic dipole attraction. Therefore, FA was added as a Fe_3O_4 dispersant to form a colloidal phase that easily dispersed into the wood and prevented coagulation, as shown in **Fig. 3b** (Kumar et al. 2010).

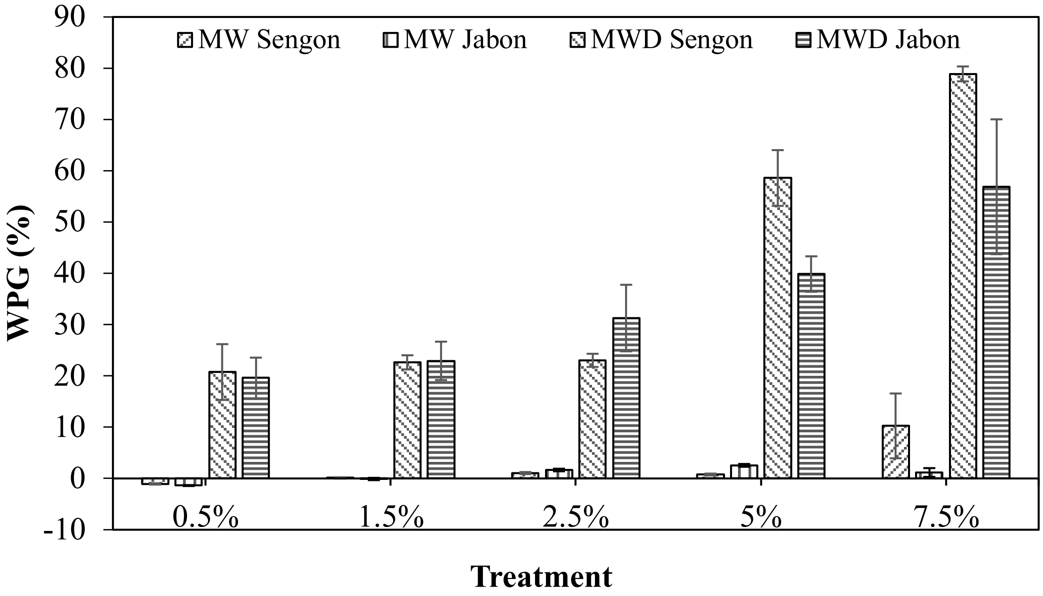

Fig. 2. The WPG of magnetic wood in various treatments.

(a) (b)

Fig. 3. (a) The solution separates into two phases, and (b) The solution forms a colloid.

The addition of FA to the impregnation solution caused a significant effect on WPG. The FA and Fe_3O_4 nanoparticles are dispersed into the colloidal phase, penetrate the wood, and form polymers between the FA, the Fe_3O_4 nanoparticles, and the chemical components of the wood. The presence of the solution can replace the free water and bound water in the cell walls (Dirna et al. 2020). According to Hill (2006), wood impregnation using polymer can cause deep penetration and easy cross-linking with the wood cell wall components. This is also supported by the result of Dong et al. (2016) that furfurylated magnetic poplar wood had a significantly higher WPG than unfurfurylated poplar wood. Rahayu et al. (2021) also stated that adding FA could distribute the nanoparticles more thoroughly into the cell wall cavities, thereby increasing the WPG.

The MWD sample also has a darker color than the MW sample. The discoloration of the wood is caused by an increase in heating temperature, which results in the degradation of hemicellulose of the wood, thus affecting the visual appearance of the wood (Rubiyanti et al. 2019; Sulistio et al. 2020). In addition, Hadi et al. (2021) stated that the discoloration of the wood indicated a polymerization process between FA, Fe_3O_4 nanoparticles, and the chemical components of the wood that were caused by the furfurylation process.

The WPG of sengon wood is relatively higher than jabon wood due to the lower initial density of sengon wood. This tendency is suspected that sengon wood has a larger cell size than jabon wood, making it easier to accommodate more solutions. Wood impregnation is a process of moving out the water or air in macropores and replaced by resin so that the cell size will have an effect (Xu and Huang 2011). According to Martawijaya et al. (2005), the pore diameter of jabon wood is 130-220 µm, and sengon wood is 140-200 µm. Based on the results of the Particle Size Analyzer (PSA) test, Fe_3O_4 nanoparticles dispersed with demineralized water have a particle size of 297±30 nm, which means that the agglomeration of Fe_3O_4 nanoparticles has a larger size compared to the pore diameter of the wood so it could not enter the wood cell wall. The pore number in jabon is 2-5 mm^{-2}, while in sengon is 1-3 mm^{-2}. This result is reinforced by the research of Prihatini et al. (2020b), stating that the smaller size of ganitri wood cells compared to jabon wood makes it harder for fluids to enter the cells. The difference in extractive content also affects the WPG. Jabon wood has a higher extractive content than sengon wood, so the permeability of jabon wood is low (Putra 2011; Sucipto and Ruhendi 2012).

The increase of WPG is directionally proportional to the increase in sample dimensions, representing the bulking effect (BE) on magnetic wood. BE is a parameter that indicates the addition of bulking process. Bulking agents can cover the wood cavities and reduce the water absorption in the wood. Therefore the dimensional stability of the wood increase (Syahidah and Cahyono 2008). **Fig. 4** shows the BE of magnetic wood after the impregnation process.

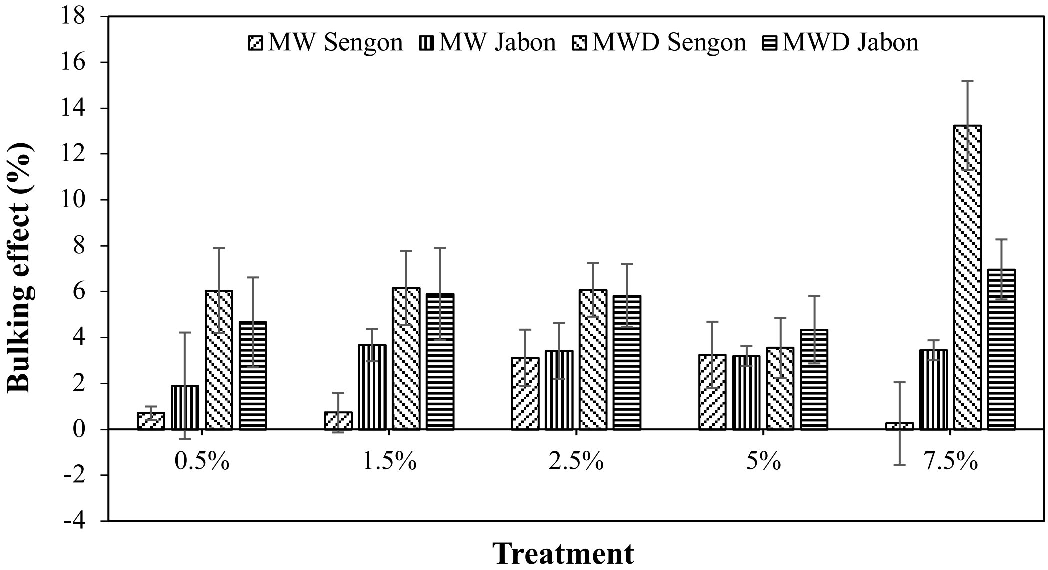

Fig. 4. The bulking effect of magnetic wood in various treatments.

In MW sample shows that the highest BE of sengon and jabon wood were obtained at concentrations of 5% (3.25%) and 1.5% (3.67%), respectively. Meanwhile, the MWD sample shows the highest BE of sengon (13.24%) and jabon (6.97%) woods were obtained at a concentration of 7.5%. The addition of FA into the wood gave a significant increase in BE compared to MWD samples. It presumably occurs because FA successfully dispersed Fe_3O_4 nanoparticles so the solution can penetrate the wood pore and bind to the wood chemical in the cell walls, resulting in a bulking effect on magnetic wood after the impregnation process. Prihatini et al. (2020a) also stated that FA combined with melamine formaldehyde was also proven successful in increasing the BE in magnetic wood. Besides increasing the weight and dimensions of the wood, FA can also increase the density of the wood after impregnation (Dong et al. 2014; 2016). **Fig. 5** shows the density of magnetic wood after the impregnation process.

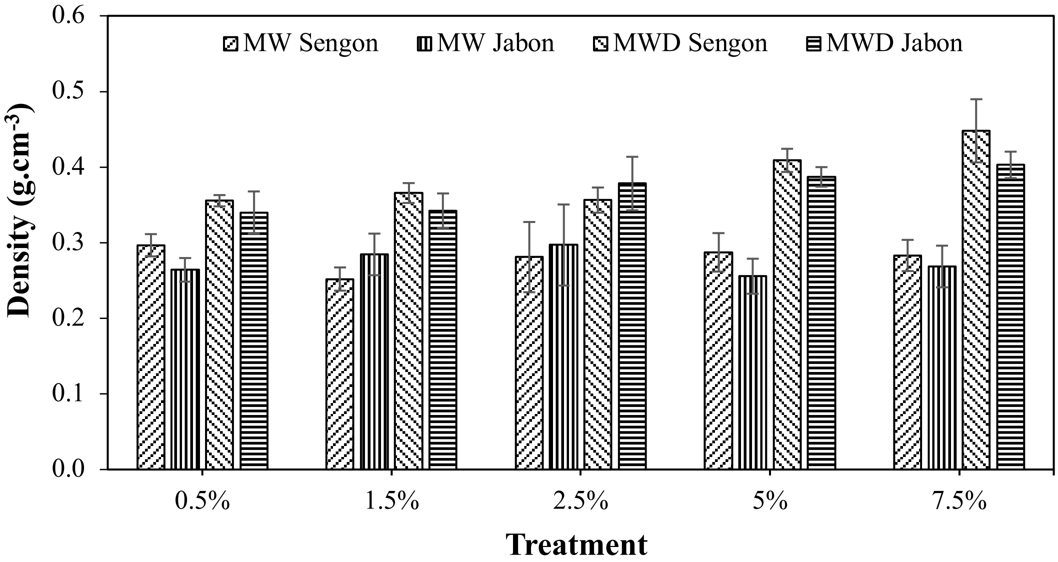

Fig. 5. The density of magnetic wood in various treatments.

According to Krisnawati et al. (2011a, 2011b), the initial density of jabon wood is 290-560 kg.m^{-3}, while the initial density of sengon wood is 230-500 kg.m^{-3}. The density of MWD tends to increase with increasing the Fe_3O_4 nanoparticles concentration. The highest density in the MW sample was obtained at concentrations of 0.5% of sengon wood (0.30%) and 2.5% jabon wood (0.30%). On the other hand, the highest density of the MWD sample was obtained at a concentration of 7.5% in both sengon (0.45%) and jabon (0.40%) wood. There is a significant difference between MW and MWD samples due to the presence of FA and Fe_3O_4 nanoparticles, which bind to the wood cell wall components, making the wood structure denser than magnetic wood without FA treatment (Rahayu et al. 2021).

3.2. The Magnetic Characteristics of Wood

The use of sensors on smartphones through the Magnetometer software can be a practical and economical method to measure the static magnetic field of the wood. Previously, magnetic field measurements using this software have been reported the results were close to theoretical measurements (Septianto et al. 2017). The results of the magnetic field strength of the wood with an observation distance of 2 cm are presented in **Fig. 6**. The concentration of 7.5% of WMD jabon wood has the highest magnetic field (51 µT). Similar results were observed in the WMD sengon wood, which reached the highest magnetic field at a concentration of 7.5% (47 µT). In addition, the magnetic field at 7.5% WM sengon and jabon can only be achieved at 32 µT and 31 µT, respectively. It proves that FA has successfully formed a colloidal phase with Fe_3O_4 nanoparticles and penetrates the cell cavities of the wood during the impregnation process. FA, Fe_3O_4 nanoparticles, and chemical components of the wood are also suspected of cross-linking in a polymerization process.

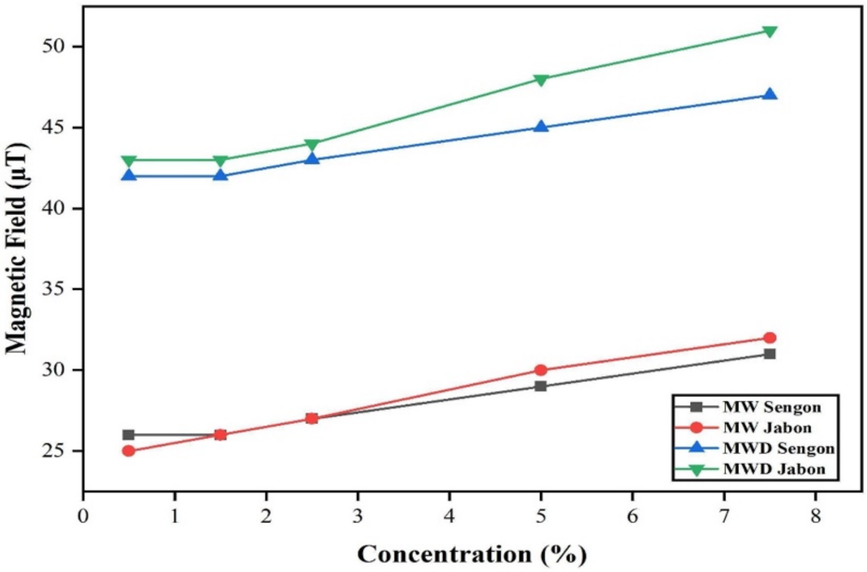

Fig. 6. The magnetic field of magnetic wood in various treatments.

The increase in magnetic field strength is linear with the increase in WPG of magnetic wood (**Fig. 7**), meaning that WPG and magnetic field strength are positively correlated. In addition, the magnetic field strength is also proven by the response of magnetic wood to permanent magnets, which was done by attaching a permanent magnet to a magnetic wood surface. The results of the response of magnetic wood to the permanent magnet are shown in **Table 1**.

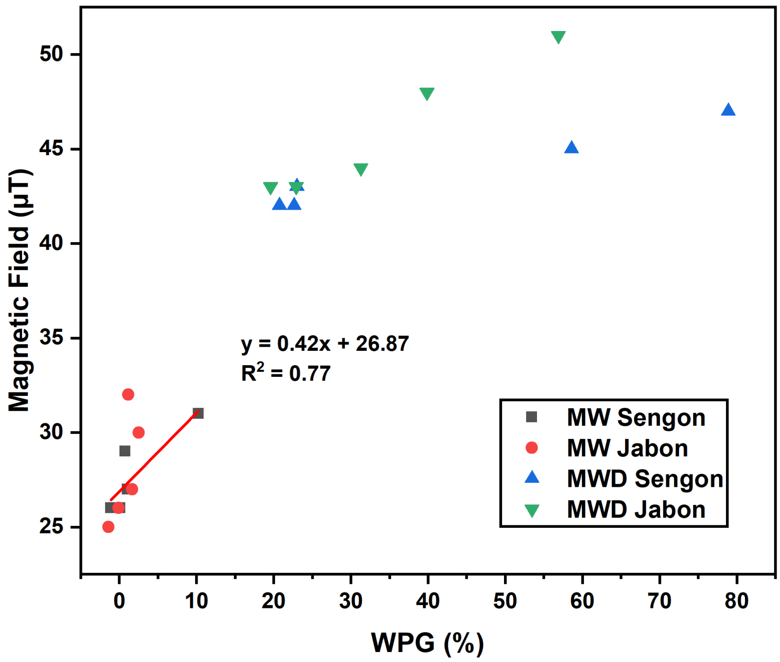

Fig. 7. The correlation between weight percent gain (WPG) and magnetic field of the sengon and jabon magnetic wood.

Based on **Table 1**, the MW samples showed a negative response to permanent magnets. On the other hand, the MWD samples began to show a positive response at a concentration of 2.5% on sengon wood and 1.5% on jabon wood. The response gets stronger with increasing Fe_3O_4 nanoparticles concentration. Jabon wood has a higher magnetic field than sengon wood because jabon wood has a higher dielectric constant and electrical conductivity than sengon, teak, and acacia wood, so jabon wood conducts electricity easier (Tang 2019).

Table 1. The magnetic wood responds to permanent magnets

Concentration	MW		MWD	
	Sengon	**Jabon**	Sengon	**Jabon**
0.5%	-	-	-	-
1.5%	-	-	-	++
2.5%	-	-	+	+++
5%	-	-	++	+++
7.5%	-	-	++++	+++++

The electrical properties and magnetic properties of the material are related. The greater the magnetic field of the material, the more its dielectric constant also increases because it is influenced by Lorenian forces, changes in the paramagnetic structure of the complex, and the Hall effect (Yang et al. 2017). The magnetic field is also influenced by distance, the farther distance used, the smaller the magnetic field produced conversely (Salomo et al. 2017; Setiawan et al. 2017). It is due to a decrease in the magnetic field gradient due to a decrease in the magnetic flux field (Septianto et al. 2017). According to Indrasari (2012), the measurement of the magnetic field is also influenced by the sensitivity of the sensor. The high-sensitive sensor will easily detect the magnetic field of the material.

Considering its easy processing, excellent magnetic properties, and increased physical properties, magnetic wood is an interesting new function for building materials, decoration, electromagnetic wave absorbers, massage furniture, and heat conductor (Gan et al. 2017; Moya et al. 2022). However, wood is an insulating material, so magnetic wood produces a relatively low magnetic field and belongs to the category of soft magnetic materials (Wahyuningtyas et al. 2022). Therefore, the magnetic wood in this study cannot be used as a permanent magnet.

3.3. FT-IR Analysis

Fig. 8 shows the FT-IR spectrum of magnetic wood, both MW and MWD samples. The magnetic wood test results showed that the Fe-O functional group identified peaks at wavenumbers 426, 561, and 433 cm^{-1}, in line with Gan et al. (2017), who stated that the vibration of Fe-O groups appeared at a wavenumber of 586^{-1}. According to Bertolucci et al. (2015) and Mohammed (2018), the absorption band of Fe_3O_4 is below the wavenumber of 590 cm^{-1}. These peaks indicate that the Fe_3O_4 nanoparticle has entered and cross-linked with the wood cell wall, increasing the wood's physical and magnetic properties (Rahayu et al. 2021). The tendency shows that the intensity peaks of the Fe-O functional group in the sengon and jabon MWD samples were sharp. This result indicates that more Fe_3O_4 was deposited in the MWD samples compared to the MW samples. The absorption area at wavenumbers of 1236 and 1039 cm^{-1} appeared in the spectrum. Nandiyanto et al. (2019) stated that these two peaks indicated the presence of C-O stretching and aromatic C-H groups. The mentioned peaks identified the broken lignin bonds due to immersion treatment of magnetic solution (Schmiedl et al. 2012).

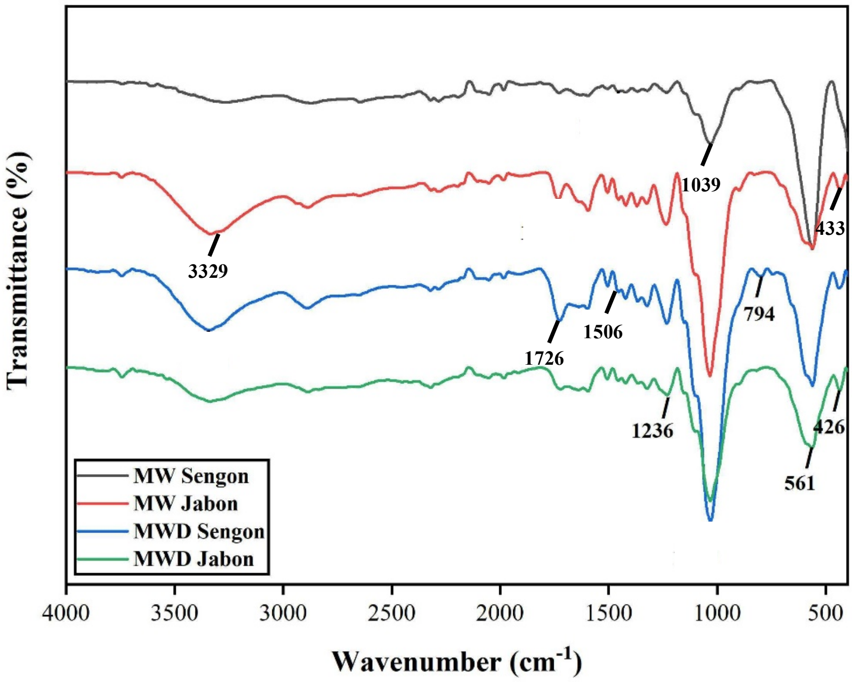

Fig. 8. The FT-IR spectra of magnetic wood (a) MWD jabon, (b) MWD sengon, (c) MW jabon, and (d) MW sengon.

There is also an absorption band peak at a wavenumber of 3329 cm^{-1}, which indicates the presence of O-H bending groups of the cellulose of magnetic wood (Coates 2006). Asriza et al. (2019) detected the O-H group at wavenumbers of 3000-3550 cm^{-1}. The presence of O-H groups in the spectrum comes from the main constituent components of wood, namely cellulose and hemicellulose (Hazarika and Maji 2014). In the MWD samples, the wavenumber of 1726 and 1506 cm^{-1} indicated the presence of the C=O stretching group vibration of the γ-diketone formed from the hydrolytic ring opening of furans as a result of hemicellulose ester bonds and lignin side chains being broken due to magnetic treatment (Dong et al. 2016). The presence of FA that cross-linked with the wood cell wall components is indicated by the vibration of a furan ring at the wave number of 794 cm^{-1}, following (Lori et al. 2011).

4. Conclusions

Magnetic wood was successfully synthesized by the Fe_3O_4 nanoparticles and FA impregnation. The addition of FA into the impregnation solution significantly affected the WPG, BE, and density of magnetic wood compared to the solution without FA addition. FA forms a colloidal phase with Fe_3O_4 nanoparticles, therefore, it can penetrate and cross-link to wood cell wall components. The addition of FA also caused the wood surfaces to become darker. The best magnetic wood treatment of both sengon and jabon was obtained on the MWD samples of 7.5%. The magnetic field of jabon wood was relatively higher than sengon wood, supported by the strongest response to permanent magnets. The results of the FTIR analysis showed the presence of furan ring and Fe-O functional groups, which bond to the wood cell wall components. Thus, this method can improve the quality of fast-growing wood and make the wood more multifunctional.

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