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# Moisture content effect on sound wave velocity and acoustic tomograms in agarwood trees (*Aquilaria malaccensis* Lamk.)

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**Abstract:** Gaharu or agarwood or oudh is a fragrant and highly valuable nontimber forest product obtained from several species of trees that produce it in response to wounding or fungal attack. The aims of the study were to evaluate the sound wave velocity change from green to dry conditions in agarwood and tomographic images associated with changes in the moisture content. A total of 10 trees were selected for this study; five trees were artificially inoculated and the other five were left untreated. After in situ measurement of standing trees stem using nondestructive testing (PiCUS sonic tomography), air-dried disk samples from the trees were assessed. The results showed that sonic velocity values increase from 12% to 22% as moisture content decreases from a green condition (live tree) to an air-dried condition (disk sample). Nevertheless, solid and damage areas revealed only slight differences on the tomograms. This research combines traditional visual assessment with tomography to better detect the presence of agarwood in trees.

**Key words:** Agarwood, moisture content, sound wave velocity, acoustic tomograph, nondestructive testing

## 1. Introduction

Currently, nondestructive testing (NDT) tools based on sound waves have been developed in the context of imaging technology (tomography) that can portray the internal condition of materials such as tree trunks (Nicolotti et al., 2003; Gilbert and Smiley, 2004; Wang et al., 2008; Wassenaer and Richardson, 2009; Lin et al., 2011; Indahsuary et al., 2014; Li et al., 2014). These technologies improve upon the single-path approach, which is limited by the lack of standard references for the comparison of sound wave velocity for estimating the conditions inside trees (Wang and Allison, 2008). Sonic or ultrasonic tomography can be applied to the trunk of a tree to distinguish intact wood and deteriorated wood based on changes in the sound wave propagation velocity matrix. This information can be used to generate a tomographic image that portrays the condition inside the tree trunk through gradations of color associated with the velocity of sound wave propagation (Brazee et al., 2011; Lin et al., 2011; Siegert 2013). Rabe et al. (2004) reported that sonic tomography can detect a decrease in the quality of wood and predecay dispersal in trees and noted that high moisture content (MC) appears to affect acoustic measurements. Meanwhile, Deflorio et al. (2008) reported significant detection of incipient stages of fungal decay in tree stems by sonic tomography.

Sound wave propagation techniques in nondestructive testing of wood are based on the duration of wave propagation passing through a medium, which can be used to calculate sound wave velocity. The concept of detecting decay or deterioration by this method arose from the observation that wave propagation is sensitive to the presence of degradation in wood. Stress wave velocity is directly related to the physical and mechanical properties of wood. In general terms, stress waves travel slower in decayed or deteriorated and hollow wood than through sound wood (Wang and Allison, 2008; Johnstone et al., 2010; Gao et al., 2014). Along with anatomical factors such as microfibril angle, density and MC also affect the sound wave propagation velocity (Bucur, 2006). Several studies have reported that stress wave velocity increases as the MC of wood decreases, and this decline will be significant in conditions below the fiber saturation point (Karlinasari et al., 2005; Oliveira et al., 2005; Hasegawa et al., 2011).

Gaharu or agarwood, also known as eaglewood or aloeswood, is a resinous, fragrant, and highly valuable heartwood produced by several *Aquilaria* and *Gyrinops* species (Tymelaeaceae) in response to wounding, fungal attack, and nonpathological processes that cause changes in the physiology and chemical production of wood (Groenewald, 2005). Agarwood-producing species are

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found only in areas from India eastward throughout Southeast Asia and in southern China, with Indonesia and Malaysia being the two major countries for agarwood production (Liu et al., 2013). Agarwood has long been important in many commodities such as medicine, perfume, and toiletry products such as soap and shampoo. In the Middle East, agarwood is known as oudh (in Arabic) and is a symbol of status, wealth, and hospitality. On the global market, prices for agarwood in consumer countries range from a few dollars per kilogram for very low-quality material to more than $30,000 per kilogram for top-quality wood (Wyn and Anak, 2010; Azah et al., 2013). The harvest of trees to obtain agarwood persists to the present day. Wood containing agarwood mostly appears dark-brown or black, and it has a characteristic fragrant scent. Various natural and artificial efforts have been used to induce agarwood production in the trunks, branches, and other parts of trees. Agarwood is collected primarily as timber, and it is traded in various forms, including chunks, particles, and powders. Sesquiterpenoid is the primary chemical component identified in agarwood, while agarospirol, jinkohol, and chromone contribute to its characteristic aroma (Ishihara et al., 1991; Liu et al., 2013). Detection of agarwood formation in standing trees, which have a high MC or green condition, has been studied using the acoustic-based NDT tool by several researchers (Ahmad et al., 2012; Indahsuary et al., 2014; Karlinasari et al., 2015). Agarwood has also traditionally been assessed in dry conditions, and the objective of this study was to evaluate the sound wave velocity changes from green to dry conditions in agarwood and the tomographic images based on changes in the MC.

## 2. Materials and methods

Ten trees of *Aquilaria malaccensis* (approximately 11 years old) from a community forest located in Prabumulih District, South Sumatra Province, Indonesia, were chosen for experimentation. The *A. malaccensis* trees had been planted among rubber plants, and inoculated and untreated trees were grown in separate locations. Five trees were wounded and artificially inoculated with the wood decay fungus *Fusarium solani* (strain FORDA-CC00500) 30 months prior to testing, and the other five trees were grown naturally and left untreated. The fungal strain that was used was known to be good for producing agarwood (Iskandar and Suhendra, 2012; Siburian et al., 2013). Agarwood trees that have been deliberately infected show agarwood formation within 3 months of the induction (Liu et al., 2013; Chong et al., 2015). The agarwood is characterized by a dark area that appears inside the trunk, and an area with very dark color corresponds to a high amount of agarwood. The success of agarwood formation is determined by the type of fungus, techniques and patterns of induction, and the length of time after inoculation of the tree.

NDT was carried out by using PiCUS sonic tomography (Argus electronic GmbH product, Rostock, Germany) at three tree heights (70, 170, 270 cm above ground level). Depending on the tree diameter, 7–12 transducers or sensors were placed around the trunk in a horizontal plane with regular spacing. Each transducer was connected to a nail imbedded in the tree trunk. Sonic wave transmission was generated by tapping nails one by one using an electronic hammer (Figure 1a). The nails served as both sending points and as receivers when they were connected to tomography sensors. The hammer was connected to the last transducer, and the first transducer was connected to a power supply that was connected to PiCUS software Q72 on the computer. Sound velocity data were captured and then transmitted to the software. A complete data matrix was obtained through this process at each testing point. The first transducer was placed at the north position and marked in order to facilitate testing of location-based activities after the trees were felled.

After completion of in situ testing on the trees, three bole sections were cut from each felled tree as 25-cm-thick disks to visually verify and document the surface condition. All sections were then shipped to the Wood Engineering Laboratory, Faculty of Forestry, Bogor Agricultural University (IPB) in Bogor, West Java; the sections were still in a green state upon arrival. After arrival, the surface of each bole section or disk sample was sanded, and the sections and samples were air-dried for 30 days using a fan. Control of the MC reduction was accomplished by periodically using a moisture tester. The NDT testing was then conducted on the disks, using the same locations as in the standing tree (Figure 1b).

Sound wave velocity across the diameter of a tree trunk reflects the condition inside the trunk. The fastest velocities indicate intact wood, while the slower sound velocities describe deteriorated areas in wood. A two-dimensional, the color tomogram was generated with each measurement. The color scale of black-brown, green-violet, and blue ranges from the fastest to the slowest velocity, indicating solid wood, early and moderate wood decay, and strongly degraded wood, respectively (Rabe et al., 2004; Göcke et al., 2010). The results from PiCUS tomography provide information about the percentage of solid wood area (So) and damage area (Dm) inside the tree, as shown by the colored areas created through sound wave velocity matrix calculations. The solid wood area (So) is considered to be intact and healthy wood, while damaged wood (Dm) is considered strongly degraded wood. The intermediate wood (Im) is defined as a transitional condition from So to Dm. The color tomogram in PiCUS showed a dark brown-black for So, beige-green to violet for Im, and violet-blue for Dm (Figure 2).

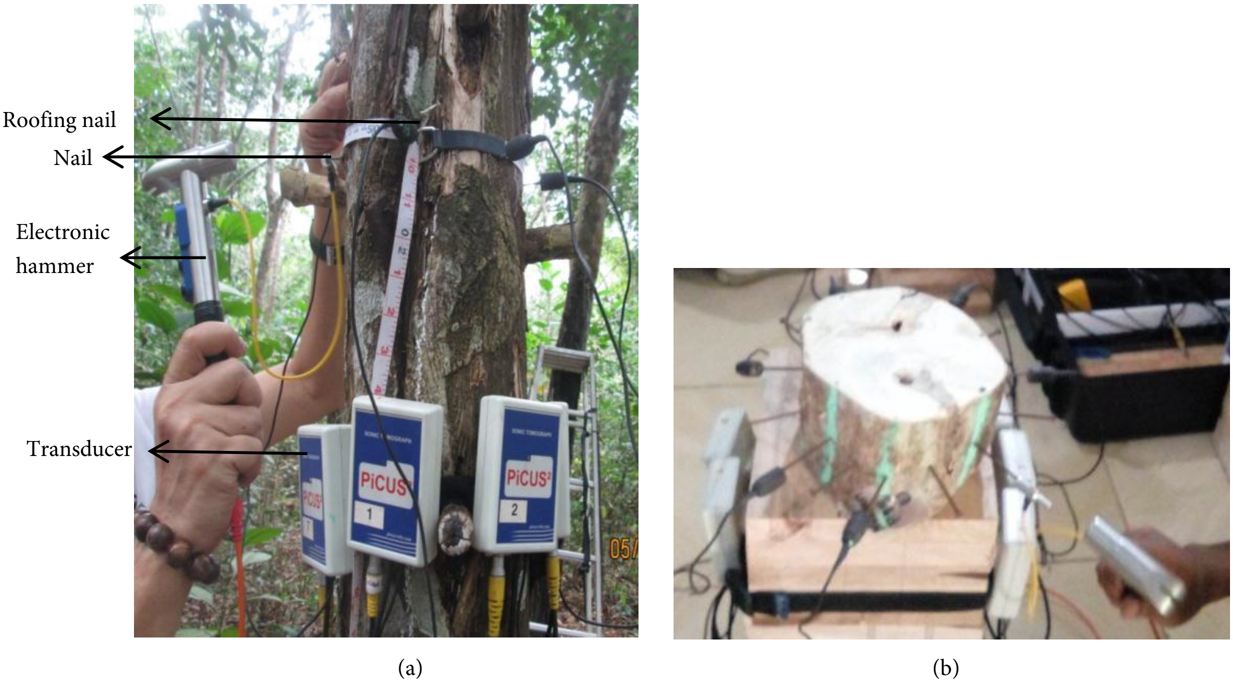



**Figure 1.** Sound wave generation activities in a standing tree (a); and in a disk sample (b).

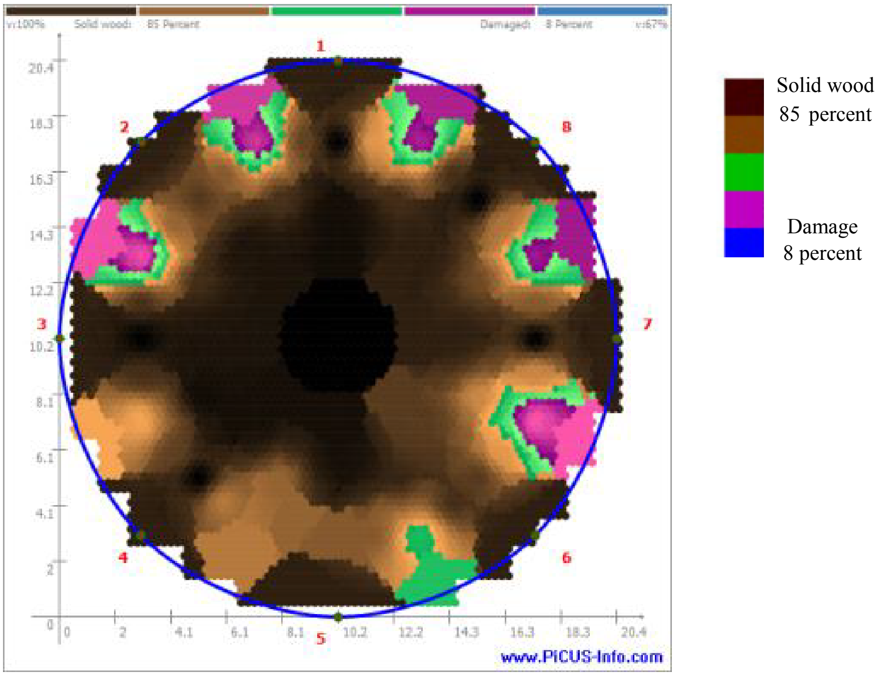



**Figure 2.** A colored tomogram showing the internal condition of the wood.

Moisture content and density of the wood were tested in green and dry conditions in this study. Green condition samples were taken from increment bore samples at 1.3 m height in standing trees. The samples were immediately wrapped in aluminum foil and transported to the laboratory. Dry condition samples were obtained from dried disks that were cut into cuboid dimensions. MC was determined according to the gravimetric method, and wood density was determined from the bulk weight and volume of the sections. A statistical comparison was carried out to evaluate the mean sonic velocity between green and air-dried conditions.

### 3. Results and discussion

In inoculated trees, agarwood formation was indicated by dark black areas, which revealed the existence of wood decay in the tree stem. Such areas can be observed visually underneath the bark (Figure 3). Resinous wood forms around these wounds after several months, and it usually produces a mild scent and slowly releases its aroma upon heating with fire.

Table 1 shows that the average diameter at breast height (dbh) of trees was 18.66 cm for inoculated trees and 21.34 cm for untreated trees. The tree height was 12.6 m for inoculated trees and 11.9 m for untreated trees. The average MC of inoculated trees was 76.9% for the green condition and 18.6% for the air-dried condition. The average MC for untreated trees was 66% for the green condition and 18.3% for the air-dried condition. Based on the physical measurements, inoculated trees had a wood density of 0.59 and 0.30 g/cm$^3$ for green and air-dried conditions, respectively. The average wood density (green condition) of untreated trees was 0.55 g/cm$^3$, and that for the air-dried condition was 0.27 g/cm$^3$. Beside the strength and duration of the scent, the product purity, resin content and color, and the wood density are important factors in the classes and prices of agarwood (Barden et al., 2000; Compton and Ishihara, 2000; Azah et al., 2013). These properties depend on chemical compounds that combine to impart an aroma when agarwood is burnt. The resin dramatically increases the mass and density of the wood containing agarwood. Chakrabarty et al. (1994) reported that the wood density of *A. malaccensis* is 0.4 g/cm$^3$.

Sound velocity characteristics and tomographic information obtained from trees and air-dried specimens are presented in Table 2. In trees, the average sonic velocity was 867 m/s (SD ± 62 m/s) for inoculated trees and 815 m/s (SD ± 73 m/s) for untreated trees. In the disk sample, the average sonic velocity was 972 m/s (SD ± 54 m/s) for inoculated trees and 1000 m/s (SD ± 116 m/s) for untreated trees. The average sonic velocity measured in the disk sample (air-dried condition) was 12% greater than that in the in situ measurements (green condition) for inoculated trees. In untreated trees, the average sonic velocity for disk samples was 22% greater than that for standing trees (Figure 4). Sound velocity is strongly dependent on the amount of water within a medium. The lower the MC, the higher the sonic velocity, especially in material below the fiber saturation point (Oliveira et al., 2005). Moreover, the ultrasonic velocity perpendicular to the fiber direction in Brazilian wood beams increased about 7% from the green condition (MC 60%) to the air-dried condition (MC 6%) (Oliveira et al., 2005). The average value of sonic velocity for untreated trees was slightly greater than that for inoculated trees, which was presumably due to untreated trees undergoing wood decay naturally caused by fungus. This finding is supported by the colored tomogram (Figure 5), which shows early detection of wood decay. However, in our study, statistical comparison analyses indicated no significant differences between the mean sonic velocity in trees (green condition) and in air-dried disk samples (P <


**Figure 3.** Dark black area on the tree stem of inoculated tree indicating the formation of agarwood in *A. malaccensis*.

**Table 1.** Tree diameter (cm), height (cm), and physical wood properties of moisture content (%) and wood density (g/cm$^3$) in green and air-dried samples

| | Diameter (cm) | Height (m) | Tree sample - green condition | | Wood disk sample - air-dried condition | |
|---|---|---|---|---|---|---|
| | | | MC (%) | Density (g/cm$^3$) | MC (%) | Density (g/cm$^3$) |
| Inoculated tree | 18.66 ± 1.23 | 12.6 ± 3.03 | 76.9 ± 25.0 | 0.59 ±0.09 | 18.6 ± 1.0 | 0.30 ± 0.02 |
| Untreated tree | 21.34 ± 3.13 | 11.9 ± 1.24 | 66.0 ± 10.0 | 0.55 ± 0.10 | 18.3 ± 7.1 | 0.27 ± 0.05 |

**Table 2.** Sound velocity (m/s) and percentage of solid, intermediate, and damaged areas in PiCUS sonic tomographs for green and air-dried condition samples.

| Tree no. | Elevation (cm) | Tree sample: green condition | | | | Disk sample: air-dried condition | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Sound velocity (m/s) | Solid area (%) | Intermediate area (% ) | Damage area (% ) | Sound velocity (m/s) | Solid area (%) | Intermediate area (%) | Damage area (%) |
| Inoculated tree | | | | | | | | | |
| 1 | 70 | 936 | 87 | 11 | 2 | 978 | 86 | 10 | 4 |
| | 170 | 853 | 82 | 14 | 4 | 893 | 93 | 4 | 3 |
| | 270 | 928 | 76 | 9 | 15 | 965 | 79 | 8 | 13 |
| 2 | 70 | 842 | 87 | 10 | 3 | 960 | 98 | 2 | 0 |
| | 170 | 938 | 85 | 10 | 5 | 943 | 97 | 3 | 0 |
| | 270 | 773 | 97 | 3 | 0 | 947 | 97 | 3 | 0 |
| 3 | 70 | 814 | 90 | 8 | 2 | 897 | 94 | 4 | 2 |
| | 170 | 758 | 89 | 9 | 2 | 915 | 86 | 13 | 1 |
| | 270 | 912 | 93 | 3 | 4 | 944 | 87 | 9 | 4 |
| 4 | 70 | 892 | 92 | 7 | 1 | 1041 | 94 | 6 | 0 |
| | 170 | 914 | 96 | 4 | 0 | 1065 | 92 | 6 | 2 |
| | 270 | 916 | 88 | 12 | 0 | 966 | 95 | 5 | 0 |
| 5 | 70 | 899 | 89 | 9 | 2 | 1055 | 88 | 10 | 2 |
| | 170 | 821 | 94 | 4 | 2 | 990 | 84 | 14 | 2 |
| | 270 | 804 | 97 | 3 | 0 | 1026 | 92 | 8 | 0 |
| | | 867 (±62) | 89 | 8 | 3 | 972 (±54) | 91 | 7 | 2 |
| Untreated tree | | | | | | | | | |
| 1 | 70 | 836 | 87 | 9 | 4 | 1321 | 93 | 6 | 1 |
| | 170 | 861 | 85 | 10 | 5 | 962 | 94 | 6 | 0 |
| | 270 | 816 | 89 | 9 | 2 | 1001 | 94 | 5 | 1 |
| 2 | 70 | 813 | 98 | 2 | 0 | 1014 | 99 | 1 | 0 |
| | 170 | 768 | 97 | 2 | 1 | 945 | 87 | 12 | 1 |
| | 270 | 789 | 89 | 10 | 1 | 971 | 92 | 8 | 0 |
| 3 | 70 | 1013 | 89 | 9 | 2 | 1152 | 92 | 7 | 1 |
| | 170 | 903 | 88 | 4 | 8 | 1040 | 91 | 9 | 0 |
| | 270 | 754 | 88 | 12 | 0 | 909 | 88 | 12 | 0 |
| 4 | 70 | 782 | 89 | 10 | 1 | 924 | 95 | 5 | 0 |
| | 170 | 728 | 87 | 9 | 4 | 877 | 90 | 7 | 3 |
| | 270 | 744 | 87 | 12 | 1 | 877 | 93 | 4 | 3 |
| 5 | 70 | 861 | 91 | 8 | 1 | 1024 | 96 | 4 | 0 |
| | 170 | 760 | 95 | 4 | 1 | 1062 | 92 | 8 | 0 |
| | 270 | 803 | 94 | 6 | 0 | 927 | 94 | 3 | 3 |
| | | 815 (±73) | 90 | 8 | 2 | 1000 (±116) | 93 | 6 | 1 |

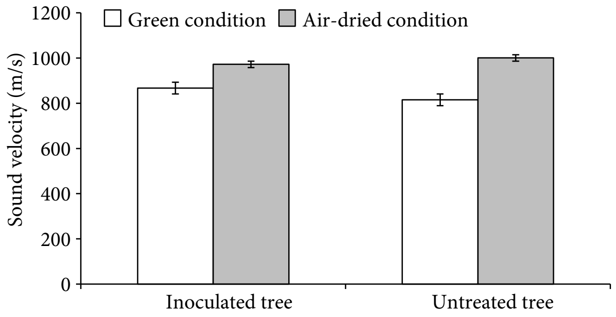



**Figure 4.** Sound wave velocity in green and air-dried wood using sonic tomography.

0.000). Tabata et al. (2003) reported that agarwood resin deposition occurred not only in trees inoculated with fungi but also in control trees.

From colored tomogram information, the percentages of solid and damaged areas were recorded as shown in Table 2. For inoculated trees, the average solid area was 89% for the green condition and 91% for the air-dried condition. In untreated trees, the average solid area was 90% for the green condition and 93% for air-dried condition. The average solid area for the air-dried condition was 1.5% to 2.7% greater than for the green condition. In contrast, the average damaged area in inoculated trees was 3% for the green condition and 2% for the air-dried condition. In the untreated trees, the average damaged area was 2% for the green condition and 1% for the air-dried condition. Compared with the damaged area for the green condition, the damaged area for the air-dried condition decreased about 0.5% to 2%. This condition was related to the matrix sonic velocity propagating across the diameter of the tree trunk. Nicolotti et al. (2003) reported that data obtained from tomography were highly correlated with the MC, which represented factors such as the presence of bound water and free water, wood cell wall composition, density, porosity, saturation, and loss of mass in the trunk tested. In addition, Bucur (2006) indicated that when water is bound in cell walls, the sonic pulse is scattered. OH units or other radicals in the cellulosic material may become reoriented under sonic stress. In this situation, attenuation

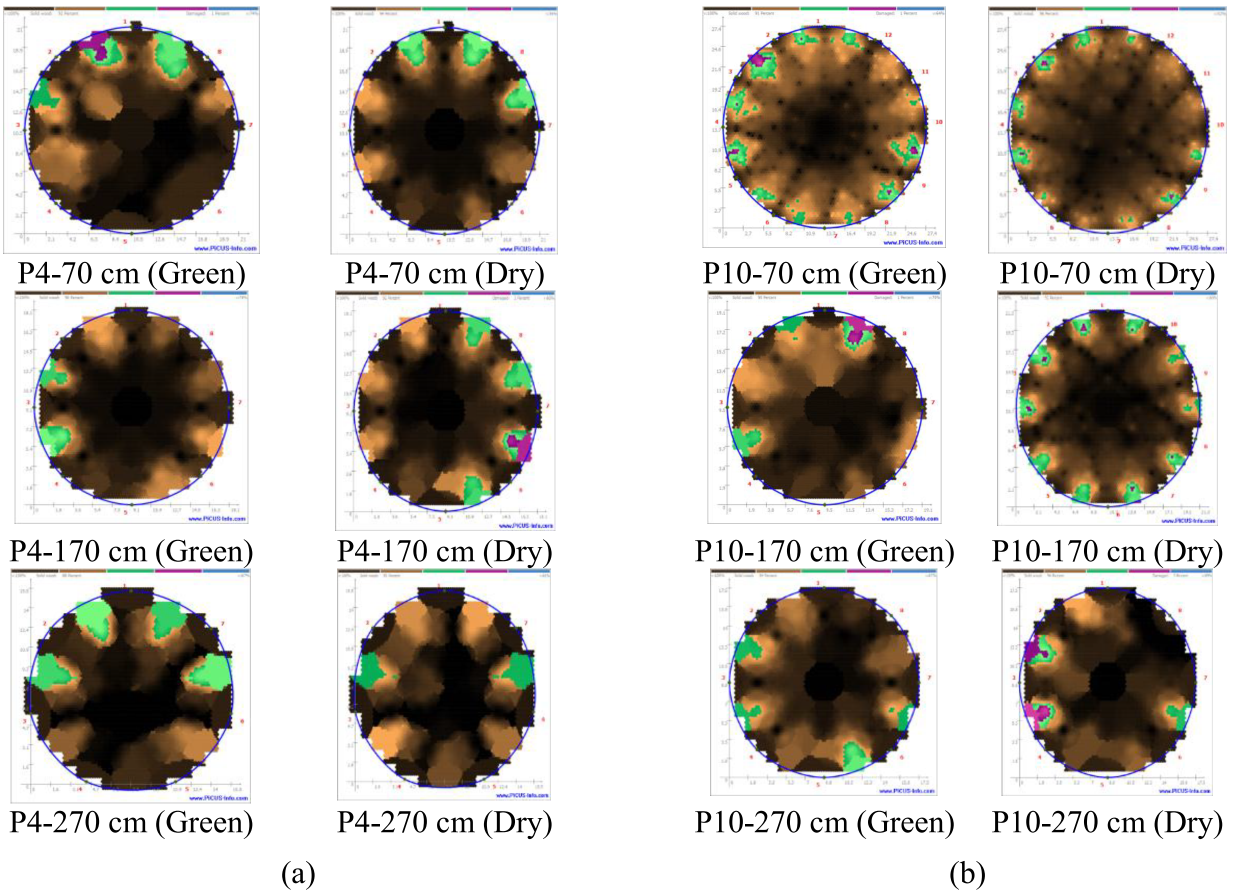


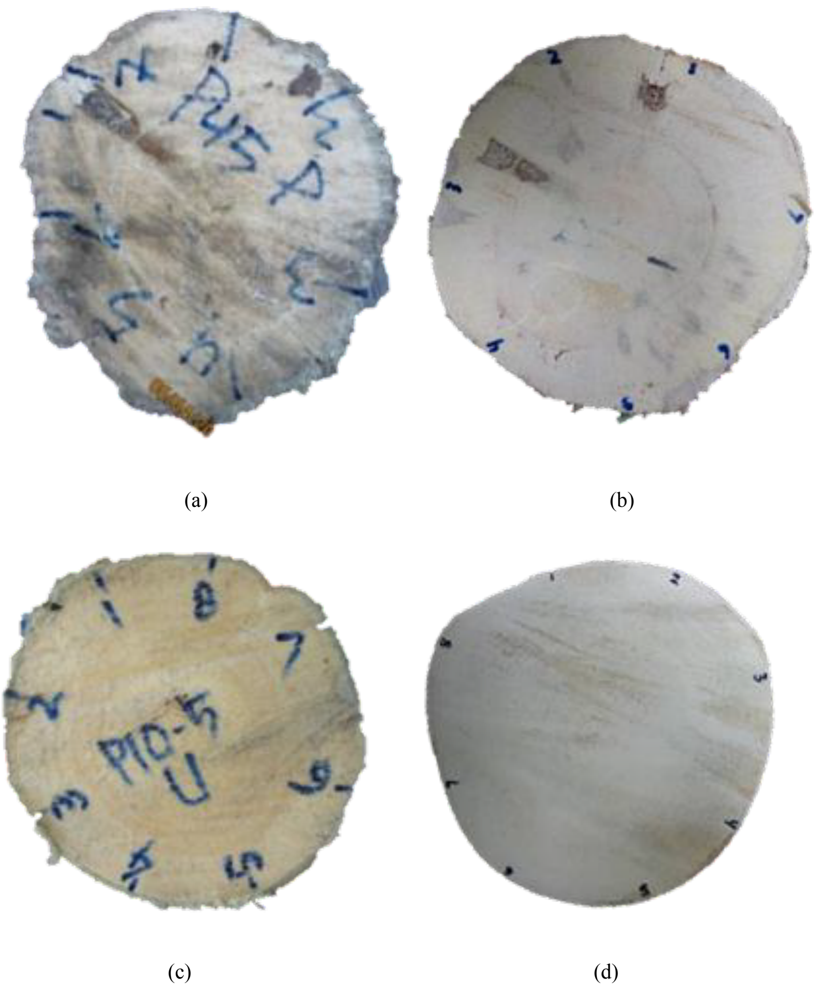

**Figure 5.** Example of colored tomogram in green and air-dried conditions: inoculated tree number P4 (a); and untreated tree number P10 (b).

of the cellulosic cell wall material is likely the most important factor. With a higher MC, but still less than the fiber saturation point, the scattering at cell boundaries could become the most relevant loss mechanism. If the fiber saturation point is exceeded and free water occurs in cellular cavities, the porosity of the material becomes the dominant factor in sonic scattering.

Wang et al. (2008) stated that acoustic tomography could not identify the type of defect found in the tree, but information related to the shape could be obtained from the colors depicted in the tomogram based on the sound waves matrix. In our study, although colored tomograms could not distinguish the type of fungal attacks within the trees, color variations were found in the tomograms of both inoculated and untreated trees that indicated wood decay advances from the stem periphery inwards (Figure 5).

A representative colored tomogram for three levels of height (70, 170, 270 cm above ground level) showed that decay significantly advances from the stem periphery inwards in an inoculated tree (Figure 5a). In an untreated tree (Figure 5b), tomograms also displayed the signs of initial stages of wood decay. This finding was confirmed after tree felling; wood decay was not apparent but discolored wood and a dark-black area in the transverse section was more clearly present in an inoculated tree (Figures 6a and 6b) compared with an untreated tree (Figures 6c and 6d). Some studies have reported that acoustic tomography tends to show the size and shape of defects as being larger than is apparent by visual inspection (Rabe et al., 2004; Liang et al., 2007; Lin et al., 2008; Wang and Allison, 2008; Wang et al., 2008). Meanwhile, Deflorio et al. (2008) advised caution in using acoustic tomography to detect the initial stages of decay advancing from the tree periphery.

Our results show that care should be taken in making conclusions about the presence of agarwood based on visual



(a) (b) (c) (d)

**Figure 6.** Transverse section after tree felling: inoculated tree number P4-270 cm in green condition (a) and air-dried condition (b); untreated tree number P10-270 cm in green condition (c) and air-dried condition (d).

assessment. Promising results on agarwood formation are indicated by colored areas on the tomograms. Therefore, predicting decay in standing trees combined with tomograms could contribute to ensuring the development of agarwood.

## 4. Conclusions

Using PiCUS sonic tomography, we found that decreasing MC from the green condition (tree sample) to the air-dried condition (disk sample) increased sonic velocity values by 12% and 22% in inoculated and untreated *A. malaccensis* trees. Nevertheless, tomographic images showed only slight increases in solid area for the air-dried condition compared with the green condition, which was opposite the decreased damage area in the air-dried condition compared with the green condition. The tomograms did not identify the type of wood decay, but could predict agarwood existence, which could not be visually detected in standing trees based on commonly used natural signs.

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