

Effects of Incision, Forced-air Drying, and Pressure Pretreatments on Wet Pockets, Drying Rate, and Drying Defects of *Acacia mangium* Wood

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The pretreatment of 7- and 10-year-old *Acacia mangium* wood using incision, forced-air drying, and pressure were conducted to evaluate the effects on wet pockets, the drying rate, and drying defects. Quarter and rift sawn boards were used in this study. Results showed that the incidence of wet pockets in the incised, forced-air drying, and pressure-treated quarter and rift sawn boards of 7-year-old *A. mangium* alleviated up to 35% and 79%, 60% and 54%, and 54% and 82%, respectively. In 10-year-old *A. mangium*, the occurrence of wet pockets was reduced by 68% and 60%, 31% and 73% and 82% and 73% in quarter and rift sawn boards, respectively. Drying rates of 7-year-old *A. mangium* pressure-treated boards increased by 5% and 40% in quarter and rift sawn boards, respectively. The drying rate was 10% faster for 10-year-old *A. mangium* pressure-treated boards. The application of the pressure pretreatment yielded no severe drying defects at the end of the drying period, except for a mild collapse in one of the 10-years old *A. mangium* sample boards. Incision and forced-air drying pretreatments improved the drying rate; however, pressure treatment was found to be superior in reducing wet pockets and drying defects.

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Keywords: *Acacia mangium*; Pretreatment; Drying rate; Wet pockets; Drying defects

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INTRODUCTION

Acacia mangium can be the primary timber source for local wood-based industries, especially for furniture, owing to its delicate appearance, grain orientation, and colour, which increase the aesthetic value of the wood. Apart from that, the quality, strength, and durability of *A. mangium* wood will bring many advantages to local wood-based industries if this wood can be utilized and managed appropriately. However, kiln-dried *A. mangium* wood has an uneven distribution of moisture contents (MC), which is a problem. The primary issue regarding the uneven drying of *A. mangium* wood is the presence of wet pockets. In timber drying, wet pockets typically occur in quarter sawn, radial-sawn, rift sawn, and double rift sawn boards and are seldom found in flat-sawn or tangential boards (Tenorio and Moya 2011; Gan *et al.* 2015).

Wet pockets, sometimes referred to as wet wood or wet spots, are abnormal zones in the heartwood with high moisture content. They occur in both softwood and hardwood. One primary characteristic of wet wood is that it dries so slowly that it is still wet when normal wood is dry. This causes variability in the final moisture content and fails to meet

requirements. The moisture content of wet pockets in *A. mangium* ranges from 12% to 76% and averages at 25% (Tenorio *et al.* 2012). It is also likely that these areas will collapse, split, or check during drying.

Most timber and lumber needs to be adequately dried to achieve a suitable quality and degree of production. As such, drying is a fundamental process in manufacturing wood. The wood drying process influences the final quality of the wood product. Dried timber needs to be defect-free, especially from honeycombing and severe surface and end checks. The dried wood must have an even final moisture content distribution to ensure dimensional stability. Uneven distribution of the final moisture content affects the quality and value of the dried timber (Elustondo *et al.* 2010).

Acacia mangium is a popular reforestation plantation tree species planted in Sarawak and throughout Asia. It has a fast growth rate, excellent wood quality, an attractive wood appearance, and tolerance to various environmental conditions (Tenorio and Moya 2011). However, *A. mangium* faces several drying setbacks, *e.g.*, the uneven distribution of final moisture contents, drying defects, and the presence of wet pockets at the end of drying. The occurrence of wet pockets causes dimensional instability in *A. mangium*. This will restrict the end uses of *A. mangium* wood, especially indoor joinery and the furniture industry applications.

Several pretreatments and methods have reportedly alleviated wet pockets and the variation in final moisture contents. Applying a hot water bath and microwave pretreatment on *A. mangium* boards before kiln drying can reduce the occurrence of the wet pockets developed after the kiln drying process (Dashti *et al.* 2012; Gan *et al.* 2015). Micro-explosion pretreatment improved the drying rate in poplar wood (Ma *et al.* 2015). Gunzerodt *et al.* (1986) introduced the wood compression method for wood treatment and preservation by improving the rate of wood drying. They applied the rolling compression method to the wood and reported that the compression method was able to enhance the permeability of the wood and the rate of the wood drying. Another wood compression method was also studied by Zhao *et al.* (2015), who applied radial and tangential compression on the wood prior to drying. They reported that the method yielded good results. The drying rate was increased due to the rupture of the pits in the wood.

Pretreatments of green eucalyptus by pre-heating, pre-steaming, microwave, pre-freezing, and boiling wood improved wood permeability, drying rate and reduced collapse during drying (Yang and Liu 2018). Chai *et al.* (2019) reported that pretreating Mongolian pine with wet air and steaming prior to high-frequency vacuum drying improved drying rate, even moisture distribution and minimized drying defects. Microwave pretreatment before conventional drying improved permeability and decreased the drying time of Chinese fir wood (Weng *et al.* 2021). Drying juvenile *Eucalyptus nitens* wood using radio-frequency vacuum without any pretreatment was shown to reduce surface checking and collapse (Ananías *et al.* 2020).

Very few studies (Dashti *et al.* 2012; Gan *et al.* 2015) have been done regarding the pretreatments of timber before drying it to alleviate the occurrence of wet pockets in *A. mangium* wood. The objectives of this study were to determine the effects of incision, forced-air drying, and pressure pretreatments on the occurrence of wet pockets, the drying rate, and drying defects in *A. mangium* dried timber. This study experimented with quarter and rift sawn *A. mangium* boards because they can develop wet pockets during drying. The information obtained from this study will establish a promising pretreatment method that can be applied to *A. mangium* timber before being dried.

EXPERIMENTAL

Sample Preparation

A total of 15 healthy and defect-free trees for both 7- and 10-year-old *A. mangium* were harvested from a forest plantation near Bintulu, Sarawak, Malaysia, with diameters at breast height (DBH) ranging from 22 cm to 32 cm. A section (billet) of 1 m long from the stump to DBH was removed from each log. From the DBH point, a clear bole of 5 m length was bucked from each tree. This study only utilized the first 5 m bole. The boles were sawn according to the “through to through” log sawing pattern (as shown in Fig. 1) with a target thickness of 30 mm. Quarter and rift sawn boards were selected for the study and processed into a standard size of 27 mm (thickness) x 150 mm (width) x 690 mm (length) (as shown in Fig. 2). This study did not include flat sawn boards because wet pockets rarely occur in tangential or flat-sawn boards (Moya and Muñoz 2008; Gan and Zairul 2011b; Tenorio *et al.* 2012).

Before subsequent pretreatment experiments, each end of the sample boards was coated with bituminous paint. The mean basic wood density (oven-dry weight/green volume) was determined for the 7- and 10-year-old *A. mangium* samples were 350 kg/m³ and 538 kg/m³, respectively.

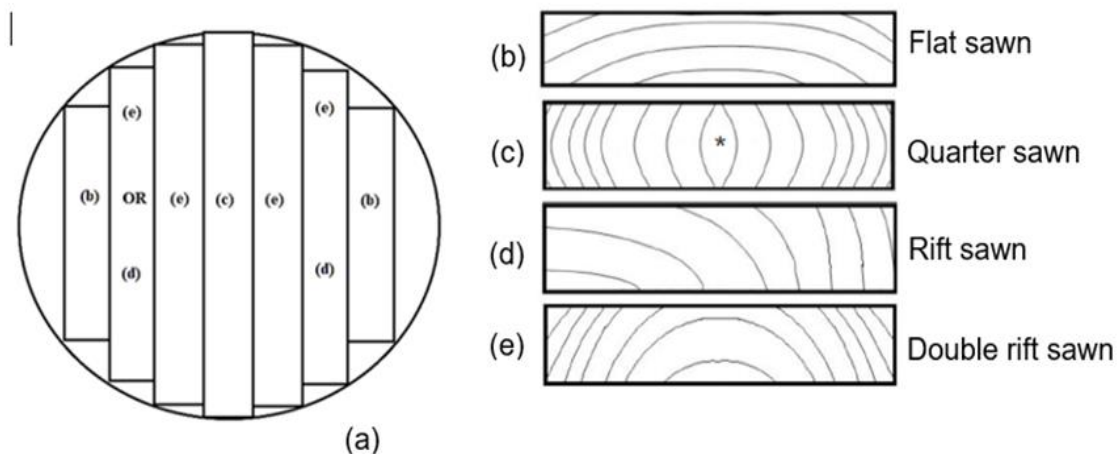


Fig. 1. Through and through or plain sawing pattern of the: (a) fresh bole; (b) flat sawn; (c) quarter sawn; (d) rift sawn; and (e) double rift sawn boards

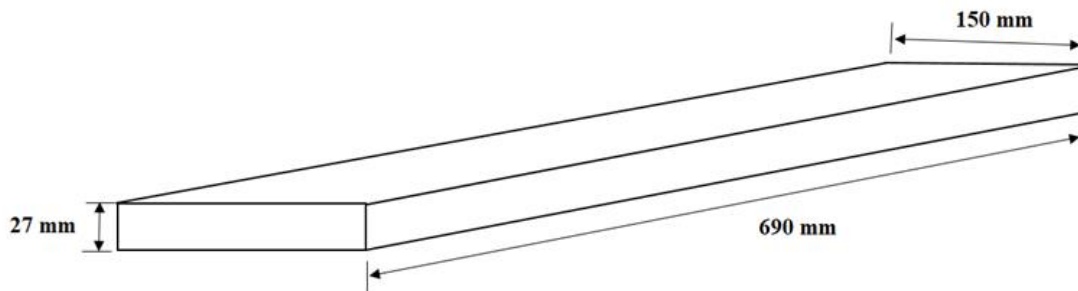


Fig. 2. The standard sample size of the quarter and rift sawn boards

Pretreatments

Incision

Incision pretreatment was carried by punching small slits into the surface of the sample boards. The incisions were only made on one surface of the sample boards (Fig. 3). By incising the surface of the boards, it is anticipated to provide passages for moisture movement during wood drying. A Jica Incision Machine was used to incise the sample boards with an incised hole depth of 10 mm.

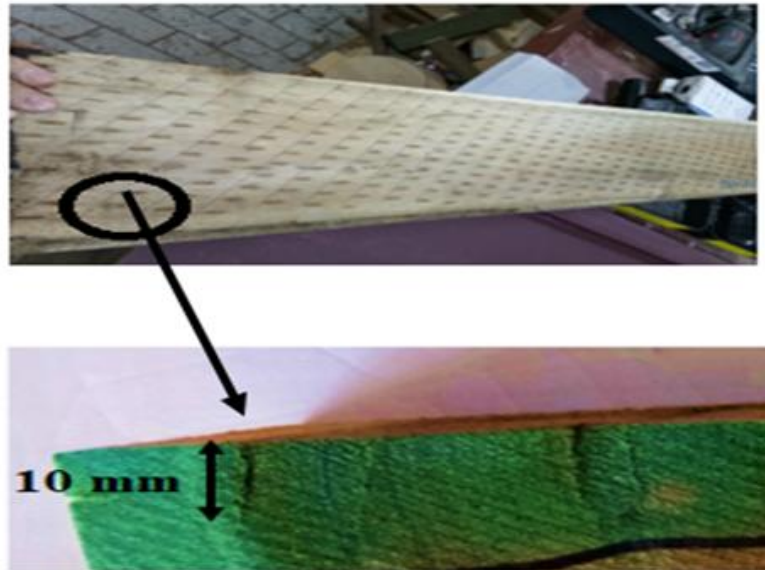


Fig. 3. Incised one side-grain sample board

Forced air-dry

The sample boards were subjected to forced air drying by using an experimental dryer fan system for a week before drying with an average air velocity of 48 m/sec. The dry-bulb temperature (DBT) and wet-bulb temperature (WBT) were both set at a temperature of 32 °C.

Pressure

This pretreatment required the boards to undergo pressure treatment, depicting a full-cell wood treatment process. The sample boards were first placed in a Jica Pressure Treatment steel cylinder, and a vacuum was applied at room temperature for 6 min to remove the air from the cylinder. Then, the pressure was applied without breaking the vacuum until it reached 150 psi and maintained at this pressure for 10 min. Finally, the pressure was released instantaneously.

Wood Drying

Following the pretreatments, all the sample boards were subjected to drying in a Hilderbrand Experimental Drying Chamber (Hannover, Germany). The drying process was carried out according to the mild drying schedule developed by Tan (2015). As shown in Tables 1 and 2, the mild drying schedules are for 7- and 10-year-old *A. mangium* boards, respectively. Each batch of drying was comprised of 12 sample boards, with 6 sample boards for quarter and rift sawn boards, respectively.

Table 1. Mild Drying Schedule for 7-year-old *Acacia mangium* Wood

Moisture Content (%)	Dry Bulb Temperature (°C)	Wet Bulb Depression (°C)	Wet Bulb Temperature (°C)	Relative Humidity (%)	Equilibrium Moisture Content (%)
> 104	47	2.5	44.5	86	17.0
104	47	2.8	44.2	83	16.2
95	47	3.4	43.6	82	15.1
85	47	4.4	42.6	76	13.5
75	47	5.6	41.4	71	11.8
65	47	7.0	40.0	63	10.5
55	4	8.8	38.2	57	9.3
45	47	11.0	36.0	48	7.9
35	47	13.0	34.0	42	6.8
30	50	15.0	35.0	37	6.2
25	57	17.0	40.0	35	5.5
20	65	18.0	47.0	35	5.4
15	70	20.0	50.0	35	4.9

Table 2. Mild Drying Schedule for 10-year-old *Acacia mangium* Wood

Moisture Content (%)	Dry Bulb Temperature (°C)	Wet Bulb Depression (°C)	Wet Bulb Temperature (°C)	Relative Humidity (%)	Equilibrium Moisture Content (%)
> 107	42	1.8	40.2	90	19.0
107	42	1.9	40.3	87	18.2
95	42	2.7	39.3	85	16.7
85	42	3.3	38.7	76	13.7
75	42	4.2	37.8	76	13.7
65	42	5.0	37.0	72	12.3
55	42	5.5	36.5	69	11.8
45	42	7.8	34.2	52	8.6
35	42	9.5	32.5	52	8.6
30	45	10.0	35.0	49	8.2
25	53	11.0	42.0	45	7.7
20	61	11.8	49.2	42	7.2
15	65	12.2	52.8	41	7.0

Determination of the Green and Final Moisture Content

The initial or green and the final moisture content were determined according to ASTM standard D4442-16 (2016). The formula for determining the moisture content is shown in Eq. 1.

$$\text{Moisture Content} = \frac{\text{Green (Initial) wt} - \text{oven dry wt}}{\text{Oven dry wt}} \times 100\% \quad (1)$$

Determination of the Area of a Wet Pocket

A strip with the dimensions of 20 mm (length) x 150 mm (width) x 27 mm (thickness) was extracted from the middle of the dried sample boards. Cobalt chloride was sprayed on the transversal section of the strips. The pinkish-brown region indicated a region with a high moisture content, which indicated a wet pocket region. Boundaries of wet pockets were delineated on the transversal section, and the wet pocket area was

determined using 2 cm x 2 cm graph paper and expressed as a per cent of the total area.

Determination of the Drying Rate

The drying period is the drying duration (in h) from the start to the termination of the drying process. The rate of drying is the measurement of the efficiency of a drying process. The drying rate was estimated by dividing the average moisture loss (%) with the drying period, as shown in Eq. 2,

$$\text{Drying rate (\%/h)} = \frac{\text{MC reduction (\%)}}{\text{Drying period (hours)}} \quad (2)$$

Determination of the Drying Defects

Drying defects were determined based on the characteristics of drying defects mentioned in Tenorio *et al.* (2012) and Listyanto *et al.* (2016). The five drying defects examined in this study were honeycombing, surface checks, end checks, collapse, and cupping.

Data Analysis

The effects of the pretreatments on the drying rate and defects were analyzed using one-way ANOVA and Tukey's multiple mean comparison test.

RESULTS AND DISCUSSION

Moisture Content

The mean initial moisture contents (MC_i), final moisture content (MC_f), and moisture loss of the quarter and rift sawn boards during the drying process for untreated and pretreated samples are shown in Tables 3 and 4 for the 7-year-old and 10-year-old *A. mangium* samples, respectively. Generally, boards from the 7-year-old wood had a higher MC_i than the 10-year-old wood. Chowdhury *et al.* (2005) showed that the green moisture content of *A. mangium* decreased with age. It is not unusual for a fresh-cut *A. mangium* timber to have more than 100% moisture content. The green moisture content of *A. mangium* at breast height from Kukut Sabah ranged from 88% to 140% (Hon 1984). The moisture contents of standing stems of *A. mangium* from Malaysia, Vietnam, and the Philippines were extremely high in the sapwood and heartwood (Yamamoto *et al.* 2003). They recorded moisture contents of 76% to 149% and 78% to 253% in the sapwood and heartwood, respectively. A high MC_i in *A. mangium* wood was also reported by Tenorio and Moya (2011) and Moya *et al.* (2011). The moisture content of freshly cut logs and green lumber ranges from 30% to greater than 200% (Glass and Zelinka 2021). The information about the green moisture content is important for harvesting and transportation equipment, procuring wood on a weight basis (such as in pulpwood), or transporting it in green condition.

After drying using the schedule recommended for 7-year-old (as shown in Table 1) and 10-year-old *A. mangium* boards (as shown in Table 2), the MC_f ranged from 8% to 15%. Generally, rift sawn boards have a lower moisture content than quarter sawn boards. Results also showed that a higher MC_i resulted in a higher moisture loss.

Table 3. Mean Moisture Content of the Pretreated and Untreated Quarter and Rift Sawn Boards of 7-year-old *Acacia mangium* Wood for the Initial, Final, and Total Moisture Loss Following Drying

Drying phase	Pretreatment							
	Untreated		Incision		Forced air-drying		Pressure	
	Quarter	Rift	Quarter	Rift	Quarter	Rift	Quarter	Rift
Initial moisture content (MC _i) (%)	120* (5.1)**	121 (6.8)	114 (5.5)	117 (6.5)	98 (4.6)	95 (3.4)	106 (2.0)	102 (5.8)
Final moisture content (MC _f)(%)	15 (2.4)	10 (1.0)	13 (2.4)	10 (1.1)	14 (2.3)	11 (2.4)	12 (2.7)	8 (0.8)
Moisture loss (%)	105 (3.9)	112 (6.8)	101 (3.4)	108 (5.9)	84 (4.5)	84 (2.0)	94 (2.0)	94 (5.4)
Note: * mean values of n = 6; and ** values in parentheses indicate the standard error of the mean								

Table 4. Mean Moisture Content of the Pretreated and Untreated Quarter and Rift Sawn Boards of 10-year-old *Acacia mangium* Wood for the Initial, Final, and Total Moisture Loss Following Drying

Drying phase	Pretreatment							
	Untreated		Incision		Forced air-drying		Pressure	
	Quarter	Rift	Quarter	Rift	Quarter	Rift	Quarter	Rift
Initial moisture content (MC _i) (%)	96* (4.1)**	104 (2.0)	101 (4.0)	109 (2.0)	96 (4.9)	86 (3.5)	114 (2.2)	99 (3.0)
Final moisture content (MC _f) (%)	11 (1.5)	12 (1.0)	10 (0.9)	8 (1.7)	14 (2.0)	8 (1.2)	11 (1.7)	11 (3.8)
Moisture loss (%)	85 (3.8)	91 (1.5)	92 (3.9)	101 (3.0)	82 (4.2)	79 (3.9)	102 (2.0)	88 (3.0)
Note: * mean values of n = 6; and ** values in parentheses indicate the standard error of the mean								

Wet Pockets in the Dried Wood

After the drying, the presence of wet pockets was detected, as there was a slightly different colour in the area of the wood with a wet pocket. The area with wet pockets had a darker colour than the wood area without wet pockets. Untreated sample boards of 7-year-old *A. mangium* developed the largest area of wet pocket, with an average of 288 cm². The smallest wet pocket was in the pressure-treated board, with an average of 122 cm², which was 58% less than the untreated sample boards. Incision and forced air-dry treated sample boards recorded lower average wet pocket areas by 37% and 34% compared to untreated boards, respectively. For the 10-year-old *A. mangium* wood, the untreated sample boards developed a larger mean wet pocket area of 380 cm². Pressure-treated, incised, and forced air-dry boards showed a decrease in the average wet pocket areas of 73%, 57%, and 6%, respectively. This study showed that sample boards with no pretreatment tended to have a larger wet pocket area after drying. Pressure pretreatment can reduce the occurrence of wet pockets in dried *A. mangium* sample boards in both 7- and 10-year-old *A. mangium* wood.

Wet pockets in heartwood contain huge moisture contents, which are 10% greater than the normal moisture content of the wood (Simpson 1991; Watanabe *et al.* 2010). The occurrence of wet pockets is high in *A. mangium* kiln-dried lumber, where 64% of the 216 boards had wet pockets (Tenorio and Moya 2011). In *A. mangium* wood, the moisture content ranged from 12% to 76%, compared to 12% to 22% outside the wet pockets (Tenorio *et al.* 2012). The amount of wet pockets usually is high in heartwood due to the extractive contents, which block the flow of water molecules through the vessels and pits. Boards from an older age of tree are prone to wet pockets remaining after the kiln drying process due to the high percentage of heartwood, whereas wet pockets were absent in lumber with high sapwood proportions (Moya *et al.* 2008).

The sawing pattern of the wood also influences the distribution of the wet pockets in the wood. Generally, rift sample boards from 7- and 10-year-old *A. mangium* wood recorded the lowest average area of wet pockets after drying compared to quarter sample boards. The orthotropic direction of the wood can influence the occurrence of wet pockets because it affects the movement of the water from the wood (Chauhan and Aggarwal 2004).

The cell arrangement in the wood varies with the orthotropic direction of the wood (Shmulsky and Jones 2019). Quarter sawn boards have radial orthotropic direction, which tends to have low permeability; thus, it is difficult for the water in the wet pocket area to diffuse out in quarter-sawn boards (Moya and Muñoz 2008). Rift sawn boards have a combination of tangential and radial orthotropic directions. In the tangential direction, the water from the wood will move out from the wood through the ray cells; thus, the movement of water is not restricted by the blocked pits in fiber (Moya and Muñoz 2008).

Pressure-treated rift sample boards recorded the lowest average area of wet pockets compared to quarter sample boards and amongst the other pretreatments (as shown in Table 5). This might be due to the changes in the anatomical characteristics of the sample boards after pressure pretreatments. The sample boards with no pretreatment tended to produce a large area of wet pockets. Pressure pretreatment alleviated wet pockets in dried *A. mangium* sample boards in both 7- and 10-year-old *A. mangium* wood.

Table 5. Mean Wet Pockets Area After the Drying of Untreated and Pretreated 7-year-old and 10-year-old *Acacia mangium* Quarter and Rift Sawn Boards

Age of the <i>Acacia mangium</i> Wood	Sawing Pattern	Pretreatment			
		Untreated	Incision	Forced air-drying	Pressure
7-year-old boards	Quarter	491* b*** (138)**	320 a (133)	196 a (121)	227 a (99)
	Rift	185 a (89)	39 a (25)	85 a (57)	17 a (11)
10-year-old boards	Quarter	629 b (78)	200 a (108)	432 a (129)	112 a (78)
	Rift	328 a (185)	130 a (40)	89 a (56)	90 a (18)

Note: * Mean values of n = 6; ** Values in parentheses indicate the standard error of the mean; and *** Mean followed by a different letter in each age row indicates significant difference at 5% level

The ability of pressure to improve the wood permeability by providing deep penetration and retention of wood preservatives is well established (Shmulsky and Jones

2019). In this study, the pressure was applied to improve water movement in the wood, reducing the incidence of wet pockets at the end of drying. Pressure pretreatment helped open up the connective wood passages by breaking down the pit membrane and intercellular spaces in the wood, which blocked the air passages. Pressure from steam explosions leads to micro-cracks on the inner cell walls, pits, and vessels of Norway spruce boards (Muzamal *et al.* 2017). Exerting high pressure to the sample boards of Chinese poplar (*Populus cathayana* Rehd) before drying, followed by the instantaneous release of the pressure, caused the pit membranes to fracture, thus increasing the wood permeability (Ma *et al.* 2015).

Drying Time and Rate

The drying times of the untreated and pretreated 7-year-old and 10-year-old *A. mangium* boards are shown in Figs. 4 and 5. The untreated 7-year-old *A. mangium* (Fig. 4) took 531 h to dry both untreated quarter sawn and incised quarter sawn boards to reach the MC_f of 15 and 13%, respectively. The longest time taken was 745 h for drying both untreated rift sawn and incised boards to attain MC_f of 10% for both test samples. The pressure-treated quarter and rift sawn boards recorded the shortest drying time (453 h) in 7-year-old *A. mangium* wood.

For 7-year-old *A. mangium* wood, the pressure-treated sample boards had the highest drying rate (Table 6). The drying rate for the pressure pretreatments was 0.21% moisture loss per hour. The incised pretreated rift-sawn boards showed the slowest drying rate, a 0.14% moisture loss per hour. Generally, the drying rate of the rift-sawn boards in the untreated and pretreated boards was considerably faster than the quarter sawn boards.

The drying time for the 10-year-old *A. mangium* boards was the same, ranging from 454 h to 478 h (19 d to 20 d) regardless of sawing patterns or treatment. The mean MC_f of the boards ranged from 8% to 14% (Fig. 9). The pressure-treated samples recorded the highest drying rate for 10-year-old *A. mangium* wood, with a mean moisture loss per hour of 0.22% and 0.19% for quarter sawn and rift-sawn boards, respectively (as shown in Table 6). Forced air drying had the slowest drying rate, 0.17% moisture loss per hour. Pressure pretreated quarter-sawn boards showed a substantial effect on improving the drying rate for 10-year-old *A. mangium* boards. An experimental drying trial of 25 mm-thick *A. mangium* using a drying oven took between 500 h and 650 h to accomplish a mean MC_f between 4.3% and 27.4% (Gan and Zairul 2011b; Gan *et al.* 2011). Using the same thickness but a schedule with higher temperatures, a kiln drying time of 337 h to 337 h was achieved, but the MC_f was greater, ranging from 9% to 52% (Tenorio and Moya 2011).

The drying rate for the boards that were pretreated with pressure was the best for both ages, especially for 7-year-old *A. mangium* wood. The pressure pretreatment in this study involved vacuuming air and water from the wood before applying air pressure and finally the rapid release of pressure. Vacuuming the wood samples was performed to remove air and water from the wood, especially in the cell wall of the wood, in order to create a difference in gradient between the layers of the wood. The existence of driving forces improved the rate of timber drying by creating a moisture gradient between the surface and centre of the wood (Espinoza and Bond 2016). The rapid release of pressure resulted in fractures in the pits in the wood cell, thus enlarging the water passage for better water movement (Zhang and Cai 2006). Ma *et al.* (2015) reported that the permeability of *Populus cathayana* Rehd wood increased when it was pretreated *via* the micro-explosion technique. Micro-explosion involves a burst of high pressure and subsequently releasing the pressure momentarily in less than 0.1 sec, resulting in a better drying rate due to the

fracturing of the pits, thus enlarging the passages for water movement in the wood. Pressure pretreatment resulted in a better rate of moisture content diffusion, which was attributed to anatomical changes in cell walls, pits, wood fibers, and connective passages in the wood.

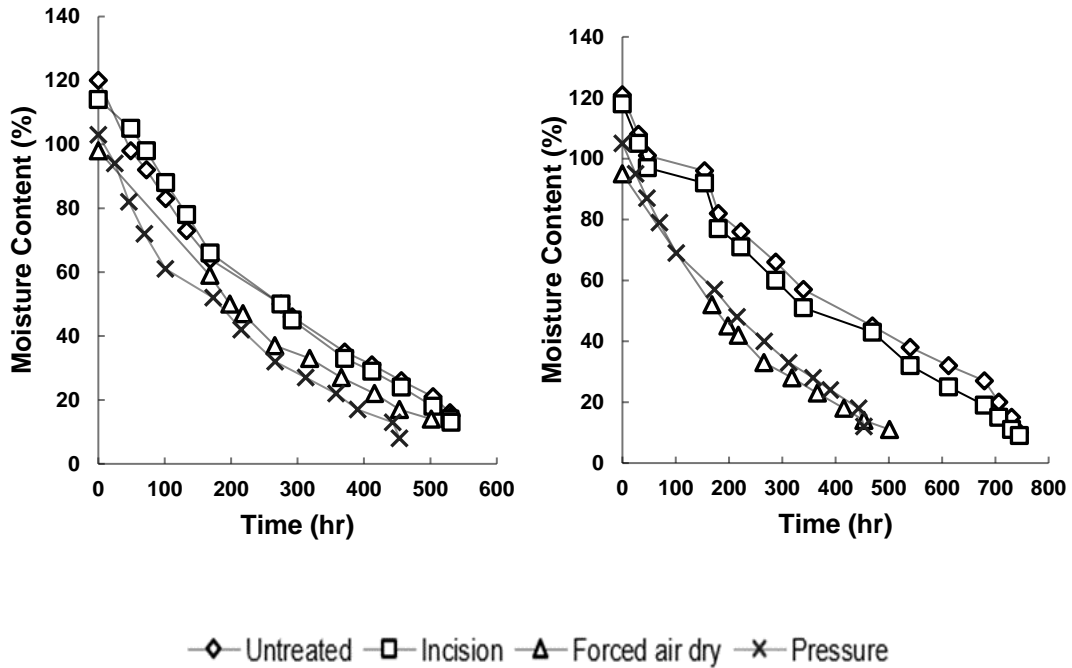


Fig. 4. The decrease in the moisture content (%) of the untreated and pretreated 7-year-old *Acacia mangium* wood: (A) quarter sawn board; and (B) rift sawn board

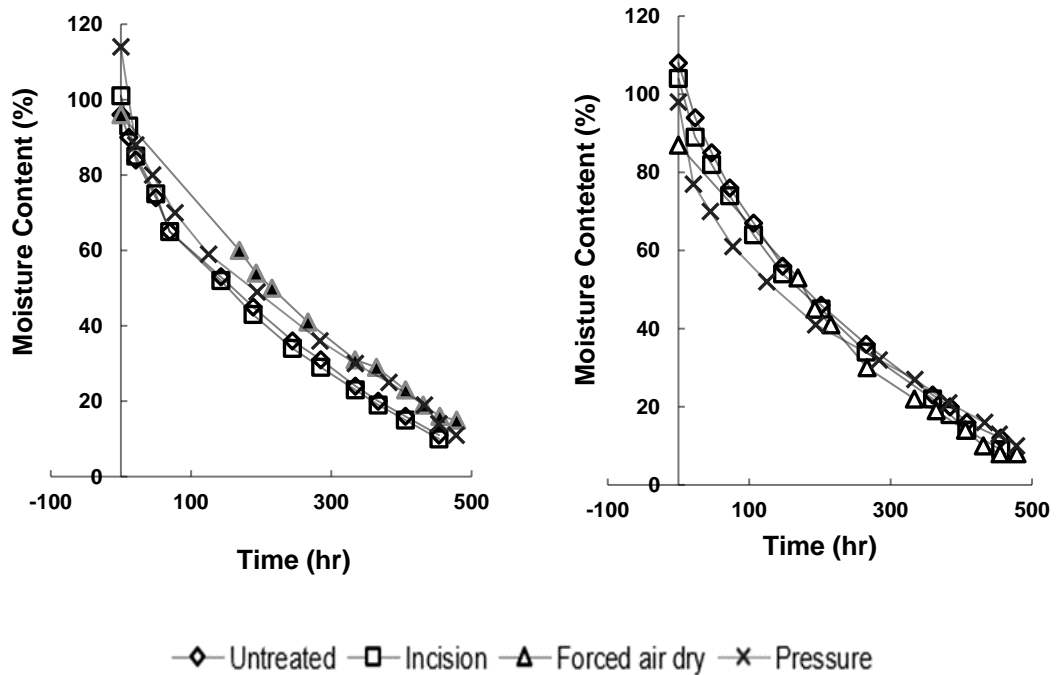


Fig. 5. The decrease in the moisture content (%) of the untreated and pretreated 7-year-old *Acacia mangium* wood: (A) quarter sawn board; and (B) rift sawn board

Table 6. Mean Drying Rate of the Untreated and Pretreated 7-Year-Old and 10-Year-Old *Acacia mangium* Wood Quarter and Rift Sawn Boards

Age of the <i>Acacia mangium</i> Wood	Sawing Pattern	Pretreatment			
		Untreated	Incision	Forced air-drying	Pressure
7-year-old boards	Quarter	0.20*cd** (0.00)**	0.18 c (0.00)	0.17 bc (0.01)	0.21 d (0.00)
	Rift	0.15 ab (0.01)	0.14 a (0.00)	0.17 bc (0.00)	0.21 d (0.01)
10-year-old boards	Quarter	0.20 bc (0.00)	0.21 bc (0.01)	0.18 ab (0.01)	0.22 c (0.00)
	Rift	0.20 bc (0.00)	0.22 c (0.01)	0.17 a (0.01)	0.19 abc (0.00)

Note: * Mean values of n = 6; ** Values in parentheses indicate the standard error of the mean; and *** Mean followed by a different letter in each age row indicates significant difference at 5% level

Drying Defects

Before the drying process, the *A. mangium* boards showed little to no incidence of twists, cups, or checks. The drying defects were only assessed after drying in the chamber was completed. The incidences of twists, cups, checks, and splits increased with the drying process (Berrocal *et al.* 2017). This study showed that certain drying defects developed in all untreated and pretreated sample boards (as shown in Tables 7 and 8).

Honeycombing and surface checks only developed in untreated 7-year-old *A. mangium* wood in both the quarter and rift-sawn boards. However, no honeycombing and surface checks were found in 10-year-old *A. mangium* wood in all pretreated boards. Surface checks only developed in untreated and incised quarter-sawn boards from 7-year-old *A. mangium* wood. There were no end checks that occurred in the 10-year-old quarter sawn and rift sawn boards. For all the 7-year-old pretreated rift-sawn boards, no end checks were observed. However, 17% and 33% of the incised quarter-sawn and forced air drying-treated boards developed end checks, respectively. Both untreated and incised boards were prone to collapse in both the quarter and rift-sawn boards of both *A. mangium* ages. Pressure-treated boards were free of collapse. Only one of the 10-years old *A. mangium* pressure-treated sample boards with mild collapse. Cupping was the most common drying defect developed in both ages of *A. mangium* wood. Even the pressure-treated boards had cupping occur.

All pretreated 27-mm thick boards developed cupping at the end of the drying period. Cupping is a common warping defect that occurs in most wood species, including *A. mangium*, and this is due to the inherent characteristics of the wood. According to Lim *et al.* (2003), *A. mangium* is prone to distortion and is highly refractory. Tenorio *et al.* (2012) indicated that 92% of the tested sample boards developed mild cupping. Warping is a common drying defect that forms after drying, especially in plantation timber, which is anticipated due to their growth stress (Lim *et al.* 2003).

This study showed mild defects, *i.e.*, cupping and surface checks, occurred in boards pretreated *via* the forced-air drying and pressure methods. The steadiness of the flow of air in the forced-air drying method helps remove the moisture above the wood, allowing the wood moisture to evaporate without causing timber tension and stress in the wood. Accelerated air drying reduces the incidence of warp and surface checks (McMillen

and Wengert 1977). Pre-drying before conventional drying could reduce the drying defect problem (Lim *et al.* 2003). In pressure pretreatment, blocked water movement is reduced due to the wood's fractured pits, cell walls, vessels, and fibres.

Table 7. Percentage of Drying Defect Incidences in 7-year-old *Acacia mangium* Wood Quarter and Rift Sawn Sample Boards

Sawing Pattern	Pretreatment	Honeycombing	Surface checks	End Checks	Collapse	Cupping
Quarter	Untreated	33*	33	0	33	83
	Incision	0	17	17	17	100
	Forced air dry	0	0	33	17	17
	Pressure	0	0	0	0	33
Rift	Untreated	17	0	0	50	76
	Incision	0	0	0	50	100
	Forced air dry	0	0	0	0	50
	Pressure	0	0	0	0	100

Note: * Mean values of n = 6 for each pretreatment

Table 8. Percentage of Drying Defect Incidences in 10-year-old *Acacia mangium* Wood Quarter and Rift Sawn Sample Boards

Sawing Pattern	Pretreatment	Honeycombing	Surface checks	End Checks	Collapse	Cupping
Quarter	Untreated	0*	0	0	17	100
	Incision	0	0	0	67	83
	Forced air dry	0	0	0	33	50
	Pressure	0	0	0	17	83
Rift	Untreated	0	0	0	33	83
	Incision	0	0	0	67	17
	Forced air dry	0	0	0	0	67
	Pressure	0	0	0	0	67

Note: * Mean values of n = 6 for each pretreatment

The 7-year-old *A. mangium* wood was more prone to drying defects than the 10-year-old wood, regardless of pretreatments, probably due to a greater amount of juvenile wood in the younger *A. mangium* wood. Chowdhury *et al.* (2005) reported that the tangential shrinkage of 10-year-old *A. mangium* wood was considerably greater than the

15- and 20-year-old wood. The increase in twist, cup, check, and split defects of *Tectona grandis* boards was related to the juvenile wood presence (Berrocal *et al.* 2017). Juvenile wood is known for dimensional instability in dried lumber due to its higher longitudinal shrinkage than normal wood (Zobel and Sprague 2012).

Among the pretreatments, the pressure and forced-air drying methods showed promising results for 7- and 10-year-old *A. mangium* wood in terms of minimizing drying defects. None of the pressure and forced-air drying pretreated boards developed severe drying defects. This may be due to the anatomical changes created by the pretreatments, allowing the water in the wood to diffuse out from the wood without force; thus, less stress developed in the wood during drying. According to Tenorio *et al.* (2012) drying defects are not affected by drying schedules but by climate, grain pattern, and the initial and final moisture contents.

CONCLUSIONS

1. Pressure pretreatment improved the drying parameters of *A. mangium* boards. The total area of wet pockets was reduced, and a higher rate of drying was obtained. In addition, the boards were defect-free with only mild collapse.
2. Incision pretreatment yielded a good drying rate in older *A. mangium* wood; however, it could not alleviate the presence of wet pockets. The boards tended to collapse at the end of the drying process.
3. Forced air drying has the lowest drying rate but was unable to reduce the occurrence of wet pockets as well as pressure pretreatment.
4. Generally, pretreatments provided a better quality of dried boards than untreated ones. This suggests that *A. mangium* wood requires pretreatment before drying.
5. Younger *A. mangium* wood appeared most likely to develop greater drying defects than older wood.

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REFERENCES CITED

- Ananías, R.A., Sepúlveda-Villaruel, V., Pérez-Peña, N., Torres-Mella, J., Salvo-Sepúlveda, L., Castillo-Ulloa, D., and Salinas-Lira, C. (2020). "Radio frequency vacuum drying of *Eucalyptus nitens* juvenile wood," *BioResources* 15(13), 4886-4897. DOI: 10.15376/biores/15.3.4886-4897
- ASTM D4442-16 (2016). "Standard test method for direct moisture content measurements of wood and wood-based materials," ASTM International, West Conshohocken, PA.
- Berrolcal, A., Moya, R., Rodríguez-Solis, A. M., and Muñoz, F. (2017). "Drying of plantation-grown *Tectona grandis* wood with daily-controlled drying rate schedule," *Journal of Tropical Forest Science* 29(1), 69-79.
- Chai, H., Xu, C. Li, J., Kong, F., and Cai, Y. (2019). "Effects of pretreatment with saturated wet air and steaming on the high-frequency vacuum drying characteristics of wood," *BioResources* 14(4), 9601-9610. DOI: 10.15376/biores.14.4.9601-9610
- Chauhan, S. S, and Aggarwal, P. (2004). "Effect of moisture sorption state on transverse dimensional change in wood," *Holz als Roh- und Werkstoff* 62, 50-55. DOI: 10.1007/s00107-003-0437-y
- Chowdhury, M. Q., Shams. M. I., and Alam, M. (2005). "Effects of age and height variation on physical properties of mangium (*Acacia mangium* Willd.) wood," *Australian Forestry* 68(1), 17-19. DOI: 10.1080/00049158.2005.10676221
- Dashti, H., Shahverdi, M. Taghiyari, H. R., Salehpur, S., and Heshmati, S. (2012). "Effects of steaming and microwave pretreatments on mass transfer characteristics of Aleppo oak (*Quercus infectoria*)," *BioResources* 7(3), 3262-3273. DOI: 10.15376/biores.7.3.3262-3273
- Elustondo, D. M., Oliveira. L., and Avramidis, S. (2010). "New methodology to optimize sorting in wood drying," *Maderas, Ciencia Y Tecnologia* 12(2), 79-91. DOI 10.4067/S0718-221X2010000200003
- Espinoza, O., and Bond, B. (2016). "Vacuum drying of wood - State of the art," *Current Forestry Report* 2, 223-235. DOI: 10.1007/s40725-016-0045-9
- Gan, K. S., Tan, J. L., and Zairul, A. R. (2011). "Drying characteristic of tropical plantation-grown timber using the proposed testing methods," in: *Proceedings of the Seminar and Workshop on Improved Utilization of Tropical Plantation Timbers*, 23-25 March, Kula Lumpur, Malaysia, pp. 107-113.
- Gan, K. S., and Zairul, A. R. (2011b). "Kiln drying of *Acacia mangium* planks pretreated in hot water," in: *Properties of Acacia mangium Planted Peninsular Malaysia*, S. C. Lim, K. S. Gan, Y. E. Tan (ed.), Forest Research Institute Malaysia, Kepong, Malaysia, 83-86.
- Gan, K. S., and Zairul, A. R. (2011a). "Drying characteristics using the standard test methods," in: *Properties of Acacia mangium Planted Peninsular Malaysia*, S. C. Lim, K. S. Gan, Y. E. Tan (ed.), Forest Research Institute Malaysia, Kepong, Malaysia, pp. 74-82.
- Gan, K. S., Zairul, A. R., and Tan, J. L. (2015). "Effectiveness of pretreatments on *Acacia mangium* for conventional steam-heated kiln drying," *Journal of Tropical Forest Science* 27(1), 127-135.
- Glass, S. V., and Zelinka, S. L. (2021). "Chapter 4: Moisture relations and physical properties of wood," in: *Wood Handbook - Wood as an Engineering Material*, U.S. Department of Agriculture Forest Products Laboratory, Madison, WI.

- Günzerodt, H., Walker, J. C. F., and Whybrew, K. (1986). "Compression rolling and hot water soaking: Effect on the drying and treatability of *Nothofagus fusca* heartwood," *New Zealand Journal of Forestry Science* 16(2), 223-236.
- Hon, C. H. (1984). "Graded sawn timber recovery study of *Acacia mangium*," *Malaysian Forester* 47(1-2), 116-124.
- Lim, K. C., Gan, K. S., and Choo, K. T. (2003). "The characteristics, properties and uses of plantation timbers- rubberwood and *Acacia mangium*," *Timber Technology Bulletin* 26, 1-11.
- Listyanto, T., Darmawan, Y. S., Pujiarti, R., Hidayati, F., Lukmandaru, G., and Sulisty, J. (2016). "Development of drying schedule of superior and conventional teak wood of 10-years old planted in Blora, Central Jaya," *Jurnal Ilmu Kehutanan* 10(1), 65-73. DOI: 10.22146/jik.12633
- Ma, Q., Zhao, Z., Wang, T., and Yi, S. (2015). "Effects of moisture on drying rate of micro-explosion pretreated fast-growing poplar wood," *Journal of Wood Research* 60(6), 899-906.
- McMillen, J. M., and Wengert, E. M. (1977). *Drying Eastern Hardwood Lumber* (Agriculture Handbook No. 528), U.S. Department of Agriculture Forest Products Laboratory, Madison, WI.
- Moya, R. R., and Muñoz, F. A. (2008). "Wet pockets in kiln dried *Gmelina arborea* lumber," *Journal of Tropical Forest Science* 20(1), 48-56.
- Moya, R., Tovar, D. A., Tenorio, C., and Bond, B. (2011). "Moisture content variation in kiln-dried lumber from plantations of *Vochysia guatemalensis*," *Wood and Fiber Science* 43(2), 121-129.
- Muzamal, M., Gamstedt, E. K., and Rasmuson, A. (2017). "Mechanistic study of microstructural deformation and stress in steam-exploded softwood," *Wood Science Technology* 51, 447-462. DOI: 10.1007/s00226-017-0896-7
- Shmulsky, R., and Jones, P. D. (2019). *Forest Products and Wood Science: An introduction, Seventh Edition*, John Wiley & Sons, Inc., Hoboken, NJ.
- Simpson, W. T. (1991). *Dry Kiln Operator's Manual* (Agriculture Handbook No. 118), U.S. Department of Agriculture Forest Products Laboratory, Madison, WI.
- Tan, J. L. (2015). "Drying characteristics," in: *Proceedings of the SFC/STA Research Seminar on Basic and Working Properties of Acacia mangium Planted in Sarawak*, Kuching, Sarawak, Malaysia, pp. 69-86.
- Tenorio, C., and Moya, R. (2011). "Kiln drying of *Acacia mangium* Willd: Consideration of moisture content before and after drying and presence of wet pocket," *Drying Technology Journal* 29(15), 1845-1854. DOI: 10.1080/07373937.2011.610912
- Tenorio, C., Moya, R., and Quessada-Pineda, H. J. (2012). "Kiln drying of *Acacia mangium* wood: Colour, shrinkage, warp, split and check in dried lumber," *Journal of Tropical Forest Science* 24(1), 125-139.
- Watanabe, K., Hart, F., Mansfield, S. D., and Avramidis, S. (2010). "Detection of wet pockets on the surface of *Tsuga heterophylla* (Raf) Sarg. by near infrared (NIR) spectroscopy," *Holzforschung* 64(1), 55-60. DOI: 10.1515/HF.2010.014
- Weng, X., Zhou, Y., Fu, Z., Gao, X., Zhou, F., and Jiang, J. (2021). "Effects of microwave pretreatment on drying of 50 mm-thickness Chinese fir lumber," *Journal of Wood Science* 67, 13. DOI: 10.1186/s10086-021-01942-2
- Yamamoto, K., Sulaiman, O., Kitingan, C., Choon, L. W., and Nhan, N. T. (2003). "Moisture distribution in stems of *Acacia mangium*, *A. auriculiformis* and hybrid acacia trees," *Japan Agricultural Research Quarterly* 37(3), 207-212. DOI:

10.6090/jarq.37.207

Yang, L. and Liu, H. (2018). “A review of eucalyptus wood collapse and its control,” *BioResources* 13(1), 2171-2181. DOI:10.15376/biores.13.1.Yang

Zhang, Y., and Cai, L. (2006). “Effects of steam explosion on wood appearance and structure of sub-alpine fir,” *Wood Science and Technology* 40(5), 427-436. DOI: 10.1007/s00226-005-0053-6

Zhao, Y. Wang, Z., Iida, I., Huang, R., Lu, J., and Jiang, J. (2015). “Studies on pretreatment by compression for wood drying I: Effects of compression ratio, compression direction and compression speed on the reduction of moisture content in wood,” *Journal of Wood Science* 61, 113-119. DOI 10.1007/s10086-014-1451-x

Zobel, B. J., and Sprague, J. R. (2012). *Juvenile Wood in Forest Trees*, Springer Science & Business Media, Berlin/Heidelberg, Germany.

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