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Effect of tree age and grain orientation on the dimensional stability of *Acacia mangium* wood from Sabah, Malaysia

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Abstract

The aim of this study was to determine the impact of tree age and grain orientation on the shrinkage and swelling of *Acacia mangium* wood. The specimens from eight ages of tree 3, 5, 7, 9, 11, 13, and 15 year-old were tested for water absorption, swelling, shrinkage, Volumetric Shrinkage and Swelling according to the ASTM D 143-94. Results show that *Acacia mangium* wood swells in both radial and tangential directions, indicating that a linear relationship can be established with increasing water content over time. At a grain angle of β = 90.0°, a significant negative correlation (R^2 = 0.98) was observed between the percentage of dimensional change and longitudinal shrinkage. There was no strong correlation (R^2 = 0.50) between the longitudinal swelling time and the dimensional change. However, a relationship (R^2 = 0.66) was indicated between the percentage of tangential and radial swelling over time at an angle of β = 0.0°. Additionally, it was investigated that the tangential shrinkage percentage of *Acacia mangium* wood increased from 0.10% to 2.758%, while the radial shrinkage increased from 0.095% to 2.385%. The findings can assist wood product manufacturers and builders in optimizing their processes to reduce warping and enhance dimensional stability.

Kewords: *Acacia mangium*, shrinkage, swelling, grain angle of wood, volumetric shrinkage

1 Introduction

Grain direction and moisture content have a major impact on the mechanical properties of wood, an anisotropic bio-porous material (Fang et al., 2021). The wooden material at the joints of the structure is consistently subjected to compression or shearing forces. Consequently, the moisture content and the orientation of the grain significantly influence the strength of wood products (Sawata, 2015; Zhao et al., 2020). Wood with varied grain directions has distinct mechanical qualities. In the longitudinal direction, wood's mechanical properties are superior to those in the transverse direction. Several investigations into how moisture affects wood's mechanical properties have been presented. Since it was introduced to Sabah, Malaysia from Australia as an exotic species in 1966, *Acacia mangium* has become one of the major fast-growing plantation species for timber and pulp production in Asia. Currently the plantation area covers over 150,000 hectares worldwide.

Botanically *A. mangium* comes from the family Leguminosae, sub-family Mimosoideae. The species are indigenous to Australia's north Queensland and can also be found in Indonesia's Moluccas Islands and Papua New Guinea. Their importance as a plantation species can be attributed to rapid growth, rather than good wood quality and tolerance to a range of soil types. The low physical and mechanical properties of young *A. mangium* wood cause the limited utilisation of the wood; therefore, specific treatment is required to enhance the wood's quality (Mulyosari et al., 2020). As grain orientation can only shrink transversely, a larger angle suggests greater longitudinal shrinkage of the wood. Juvenile wood experiences a reduction in length as the grain angle increases from the pith to the bark (Tamer A. Tabet and Fauziah Abdul Aziz, 2010). A strong negative correlation was found between density and shrinkage properties. In contrast, the relationship between grain orientation and anisotropic shrinkage was positive. Wood usually has grain that runs parallel to the stem's longitudinal axis. Nonetheless, differences in grain orientation can be seen both throughout the height of the stem and within the tree's cross-section. Wood develops helical, interlocking, and wavy grains because of this variation in grain orientation in both axial and radial directions. The timber industry frequently saws a log precisely along its grain to achieve maximum strength and form stability (Sotannde, 2010). One of the main causes of surface checks, warping, and other drying problems has been identified as unequal shrinkage across the wood sections. Additionally, earlywood is known to have a more noticeable transverse shrinkage anisotropy than latewood (Bonarski et al., 2015). The hygroscopic middle lamella plays a significant role in tissue-level deformation, as evidenced by the variations in shrinkage and swelling observed at different hierarchical levels, including tissue, cell, and fibre orientations. By optimising its hierarchical structures, the complex system of wood likely possesses the capacity to regulate hygroscopic deformations (Zhan et al. 2021). Shrinkage appears to fluctuate somewhat (mostly reductive for radial shrinkage) from pith to bark direction, but not significantly (M Chavenetidou et al., 2020).

The trees were chosen at different ages because of their abundance and excellent adaptation to the local ecological conditions of the region. Therefore, it is anticipated that the study's findings will offer baseline data regarding the prospective use of *A. mangium* wood in structural and building projects. There is no extensive literature about *A. mangium* wood; therefore, this paper tries to fill the gap by providing fresh insights into the anisotropic shrinkage and swelling in *A. mangium* wood along the grain. Understanding the anisotropic shrinkage and swelling behavior can inform better utilization of *A. mangium* wood in construction and furniture-making applications.

2 Materials & Methods

2.1 Shrinkage and Swelling Sampling Method

The samples for the shrinkage and swelling measurements were prepared from a 50 cm trunk taken from each tree of *A. mangium* in the longitudinal, tangential and radial directions as described in the diagram shown in Figure 1. Samples were cut from the same area of the impact samples of the trunk, which are pith, bark and pith-bark considering the difference in the diameter of wood disc for each age. Three blocks were cut from each disc using an electric saw, the dimensional length in the longitudinal, tangential and radial directions were made as 10 mm, 20 mm and 20 ± 0.1 mm. Direction of the grain with respect to the vertical axis of the trunk was considered to investigate the relationship between grain orientation and shrinkage and swelling (Figure 2). Diameter at Breast Height (DBH) was used to cut wood discs from each trunk of *A. mangium* trees aged 3, 5, 7, 9, 11, 13, and 15 years, as illustrated in Figure 3.a. A wood trunk measuring roughly 20 cm in diameter was prepared at DBH from a 9-year-old *A. mangium* tree, which was used as the model for data analysis in this manuscript as shown in Figure 3.b. A fly cutter was used to cut samples with respect to the grain angle. Figure 3.c. shows wood block measured 10 mm × 20 mm × 20 mm at grain angle w = 50° ± 0.5°, which was cut from the pith-bark region at about 50 mm ± 0.5 mm from the pith to clear knots in the wood. Finally, thin samples were sliced with a microtome to be observed using optical microscopy for three-dimensional surface measurements using the Infinite Focus Alicona IFM G3 to investigate the morphology of the samples (Figure 4).

2.2 Grain Orientation Measurement

The direction parallel to the longitudinal axis of most of the tapered wood is called the grain direction. Wood grains normally have their orientation essentially parallel to the longitudinal axis of the stem. But in many cases, grain orientation is at a slight angle to the longitudinal axis of the stem. Grain orientation was measured manually. In this investigation, the orientation of the growth rings was determined by visually inspecting the wood samples and using a hand plane to feel the grain. This conventional method involves measuring the grain orientation angle after visually identifying the wood grain by searching for straight, parallel growth rings that run vertically in quarter-sawn boards (Szymon Bijak and Hubert Lachowicz, 2021). The grain orientations in the inner wood (heartwood) and outer wood (sapwood) were measured with respect to the longitudinal axis of the sampling discs. Each billet's bark was peeled and polished with an orbital sander to make the grain direction noticeable to determine the outer wood grain angle.

2.3 Dimensional changes

The oven-dry method was employed in this study as the most accurate means of determining moisture content, which is essential for understanding dimensional changes. This process entails weighing an oven-dry wood sample and placing it in a ventilated oven at a temperature of approximately 103 degrees Celsius until it reaches a constant weight.

2.4 Configuration of Testing Specimens

The configurations of different testing specimens are shown in Figure 1. The dimension of the testing specimen was 10 mm × 20 mm × 20 mm (width × depth × height).

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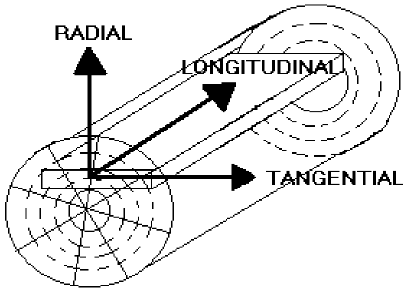


Figure 1: Diagram illustrating the radial, tangential and longitudinal directions of *A. mangium* sample.

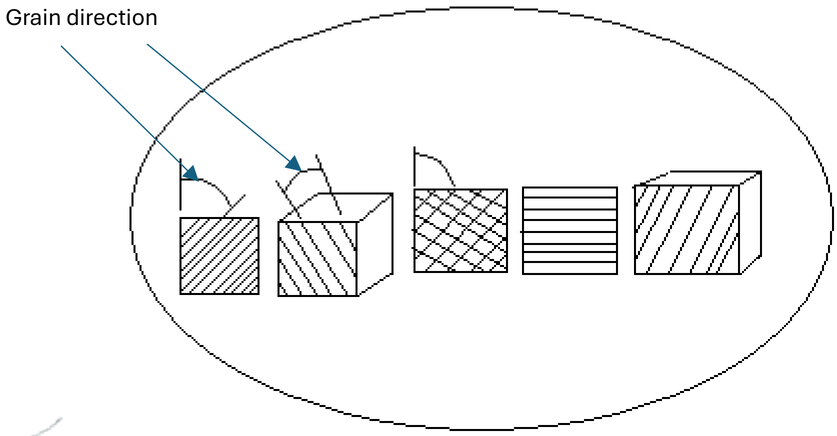
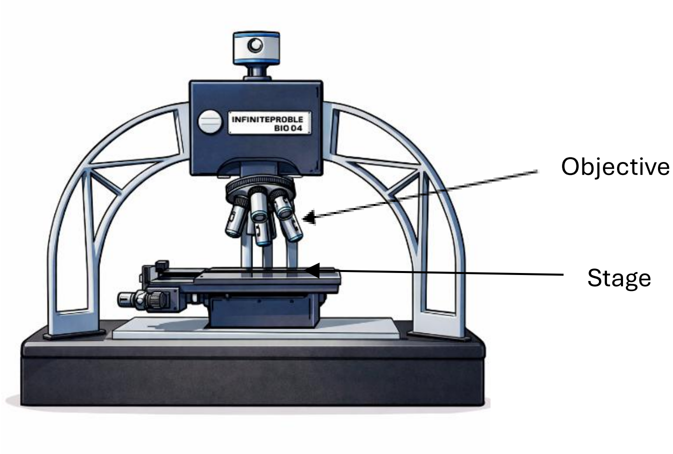


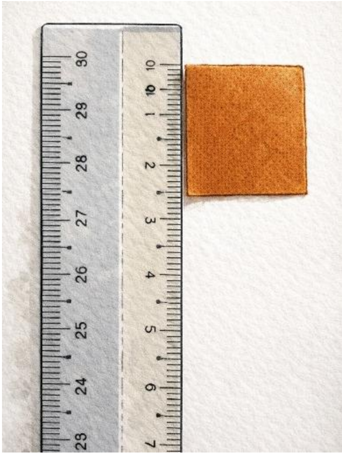
Figure 2: Diagram explaining the configurations of testing specimen.

(a) (b) (c)

Figure 3: (a) Wood discs from *A. mangium* trees, aged 3, 5, 7, 9, 11, 13, and 15 years, arranged from top to bottom. (b) Wood trunk from a 9-year-old *A. mangium* at DBH and diameter around 20 cm (c) Wood block measured 10 mm x 20 mm x 20 mm and angle β = 50° ± 0.5 from pith-bark region in tangential direction.



(a)



(b)

Figure 4: (a) 3-D Optical Microscope, Infinite Focus alicona. Hi-Tech Instrument Sdn Bhd. Teslastrabe 8, A-8074 Grambach / Graz. Austria. (b) wood sample 20mm (length) x 50 µm (thickness) for morphology test.

2.5 Volumetric Shrinkage and Volumetric Swelling

The volumetric swelling was calculated according to the following equation:

$$\alpha_v = \alpha_{rad} + \alpha_{tg} + \alpha_{lg} + \frac{\alpha_{rad}\alpha_{tg}}{100} \quad (1)$$

where:
α_v = the volumetric swelling %,
α_{rad} = radial swelling %,
α_{tg} = tangential swelling %
α_{lg} = the longitudinal swelling %

Volumetric shrinkage was calculated according to the following equation:

$$\beta_v = \beta_{rad} + \beta_{tg} + \beta_{lg} - \frac{\beta_{rad}\beta_{tg}}{100} \quad (2)$$

where
β_v = the volumetric shrinkage %,
β_{rad} = radial shrinkage %,
β_{tg} = tangential shrinkage %
β_{lg} = the longitudinal shrinkage %.

2.6 Statistical analysis and data processing

Regression analysis was used to model the relationship between the tangential and longitudinal swelling/shrinkage and grain orientation in *A. mangium* wood at different ages. The results of a 15-year-old tree are presented in this paper. Correlation analysis was performed to evaluate the strength of the relationship between the variation of longitudinal swelling with tree age of *A. mangium* wood, as well as the variation of volumetric swelling and shrinkage with grain angle.

3 Results

In this study, we examined the relationship between the grain orientation and swelling and shrinkage characteristics of *Acacia mangium* wood. The longitudinal, tangential and radial shrinkage and swelling were determined as a function of the grain orientation in wood samples of 3, 5, 7, 9, 11, 13 and 15-year-old.

3.2 Data Analysis

The swelling dimensional changes in the tangential, radial and longitudinal directions for the wood samples at angle β = 0.0°, with respect to the grain orientation are presented in Table 1. Table 2 shows the dimensional changes due to shrinkage in the tangential, radial, and longitudinal directions for the wood samples at an angle of β = 0.0°. The experimental results illustrated that tangential swelling increased from 0.653% to 6.084%. The radial swelling increased from 0.215% to 4.113% while the longitudinal swelling increased from 0.10% to 0.69% at β = 0.0°, as shown in Table 3. Results also show that the tangential shrinkage increases from 0.552% to 8.663%. It is always greater than radial shrinkage which increases from 0.368%

to 4.278% at an angle of 0.0° while longitudinal shrinkage increases from 0.11 % to 0.69 % (Table 1). There are two possible reasons for this difference. First, wood contains passages that run from the pith to the bark; these passages are known as rays and are relatively abundant. If the fibres are joined to the rays, they anchor the fibres in place. The rays don't hinder but rather assist with swelling and shrinkage in the tangential direction. The second potential explanation for the varying degrees of swelling and shrinkage observed in the variations in the radial, tangential, and longitudinal directions can be attributed to the different capacities of earlywood and latewood within the wood trunk to swell and shrink. Additionally, Cell layout, especially the alternation of earlywood and latewood, has a significant impact on the functioning of cells at the microscopic level (Murata and Masuda 2006). When these processes are combined in early and late wood, the overall shrinking and swelling of the wood is the consequence. But when they are apart, they behave differently. One tree species (with certain grain direction) showed a greater shrinkage of the earlywood in some samples and a smaller shrinkage of the latewood in others (Nikolay Bardarov et al., 2024). At β = 90.0°, it was observed that shrinkage and swelling occur predominantly along the fibres, with only a minor percentage of tangential and radial shrinkage or swelling.

The results showed that for an increase in β of 0.0° ±0.5° to 90.0°, the αv decreased from 11.734 % to 7.311 %. As Table 6 illustrates, β_v drops from 13.594% to 8.302% due to the comparable change in grain angle β. Figure 13 shows that αv and βv remained constant with only a slight variation at angle β =90.0°. The results indicate that the minimal value of volumetric shrinkage in *Acacia mangium* is 8.302, while the saturation point of volumetric swelling is 7.311%. For every value of fiber orientation β, the values of αv and β_v were computed and shown in Table 6.

Table 1: The swelling dimensional changes in tangential, radial and longitudinal directions for *A. mangium* samples at β = 0.0°

Tangential samples	Dimension (mm)	Weight (gram)	Time (minute)	Interval time (hour)	Radial. (dimension) mm	Longitudinal (mm)
1	19.125	6.460	10.0	From 0-1	19.041	10.010
2	19.150	6.490	20.0		19.123	10.017
3	19.315	6.510	30.0		19.210	10.030
4	19.380	6.531	40.0		19.270	10.036
5	19.431	6.560	50.0		19.310	10.040
6	19.480	6.581	60.0		19.340	10.045
7	19.50	6.600	90.0	From 1-5	19.350	10.051
8	19.530	6.610	120.0		19.371	10.056
9	19.610	6.630	150.0		19.420	10.059
10	19.750	6.683	180.0		19.480	10.061
11	19.840	6.700	210.0		19.492	10.064
12	19.892	6.720	240.0		19.510	10.066
13	19.910	6.750	270.0	From 5 -10	19.521	10.067
14	19.980	6.790	300.0		19.539	10.068
15	19.995	6.810	360.0		19.551	10.068
16	19.992	6.8150	420.0		19.563	10.068
17	20.000	6.820	480.0		19.577	10.068
18	20.050	6.837	540.0		19.591	10.068
19	20.050	6.841	600.0		19.635	10.068
20	20.089	6.850	660.0	From 10-20	19.670	10.068
21	20.098	6.881	720.0		19.689	10.068
22	20.127	6.900	780.0		19.713	10.068
23	20.133	6.940	840.0		19.737	10.068
24	20.139	6.972	900.0		19.759	10.069
25	20.141	6.983	960.0		19.764	10.069
26	20.145	7.010	1020.0		19.775	10.069
27	20.165	7.051	1,080.0		19.788	10.069
28	20.200	7.090	1,140.0		19.792	10.069
29	20.231	7.142	1,200.0		19.815	10.069

Table 2: The shrinkage dimensional changes in tangential, radial and longitudinal direction for *A. mangium* samples at β =0.0°.

Tangential samples	Dimension (mm)	Weight (gram)	Time (minute)	Interval time (hour)	Radial (dimension) mm	Longitudinal (mm)
1	18.895	6.310	10.0		18.930	9.989
2	18.871	6.300	20.0		18.985	9.957
3	18.653	6.294	30.0		18.90	9.943
4	18.780	6.287	40.0	0-1	18.851	9.934
5	18.431	6.281	50.0		18.750	9.932
6	18.280	6.274	60.0		18.491	9.932
7	18.200	6.262	90.0		18. 450	9.932
8	18.110	6.258	120.0		18.413	9.932
9	17.983	6.251	150.0		18.395	9.932
10	17.879	6.243	180.0		18.377	9.932
11	17.865	6.238	210.0	1-5	18.358	9.932
12	17.830	6.229	240.0		18.335	9.932
13	17.801	6.213	270.0		18.317	9.932
14	17.788	6.201	300.0		18.296	9.932
15	17.703	6.195	360.0		18.283	9.932
16	17.681	6.184	420.0		18.270	9.932
17	17.610	6.177	480.0	5 -10	18.257	9.932
18	17.587	6.168	540.0		18.246	9.932
19	17.545	6.145	600.0		18.220	9.931
20	17.503	6.132	660.0		18.215	9.931
21	17.485	6.127	720.0		18.211	9.931
22	17.467	6.119	780.0	10-20	18.207	9.931
23	17.458	6.111	840.0		18.198	9.931
24	17.449	5.991	900.0		18.193	9.931
25	17.418	5.972	960.0		18.190	9.931
26	17.395	5.963	1020.0		18.189	9.931
27	17.387	5.951	1,080.0		18.188	9.931
28	17.366	5.933	1,140.0		18.187	9.931
29	17.354	5.947	1,200.0		18.187	9.931

Table 3: The Percentage of swelling versus time for *A. mangium* wood at fibre angle β = 0.0°

Time (minute)	Tangential swelling (%)	Radial swelling (%)	Longitudinal swelling (%)	Tangential/Radial
10	0.653	0.215	0.10	3.037
30	1.630	1.109	0.30	1.469
60	2.464	1.758	0.45	1.401
300	4.904	2.758	0.68	1.778
600	5.236	3.234	0.68	1.619
900	5.655	3.841	0.69	1.472
1,200	6.084	4.113	0.69	1.480

Table 4: The Percentage of shrinkage versus time for *A. mangium* wood at fibre angle β = 0.0°.

Time (minute)	Tangential shrinkage (%)	Radial shrinkage (%)	Longitudinal shrinkage (%)	Tangential/Radial
10	0.552	0.368	0.110	1.50
30	1.805	0.510	0.430	3.166
60	3.789	2.678	0.680	5.572
300	6.378	3.705	0.680	1.721
600	7.657	4.105	0.680	1.865
900	8.163	4.247	0.690	1.922
1,200	8.663	4.278	0.690	2.025

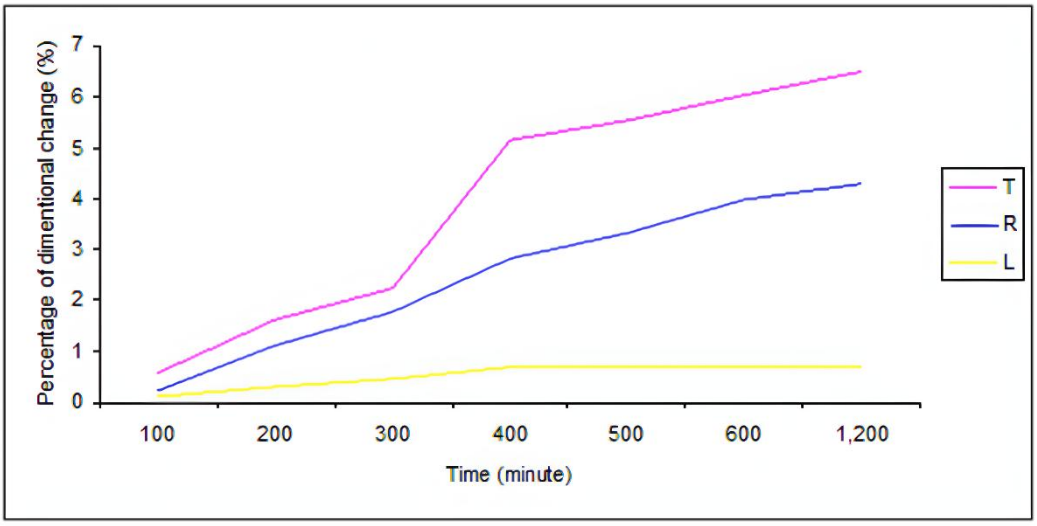


Figure 5: The percentage of swelling over time according to the experimental directions at β = 0.0°.

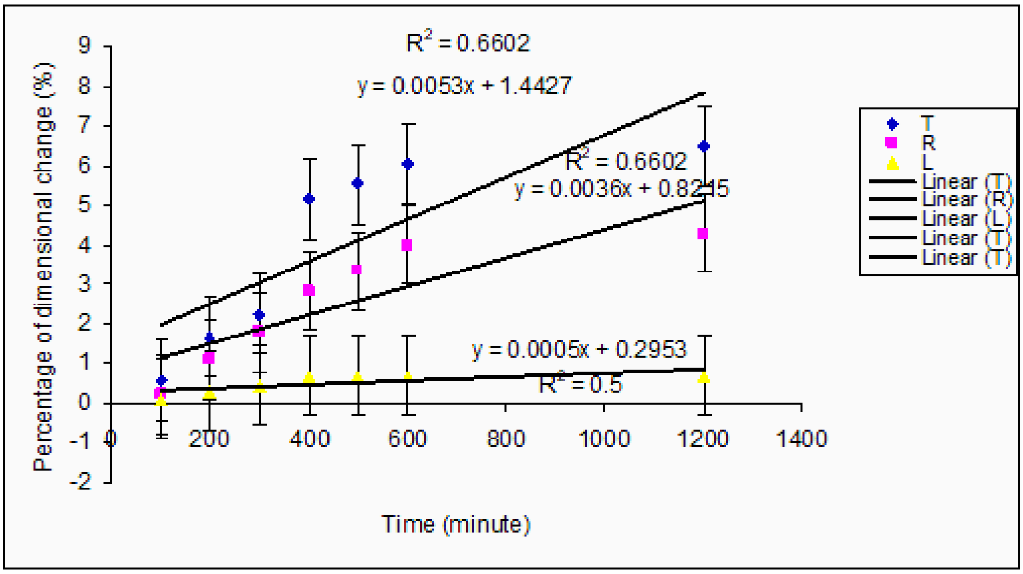


Figure 6: The error bar of the percentage of swelling over time at angle β = 0.0°.

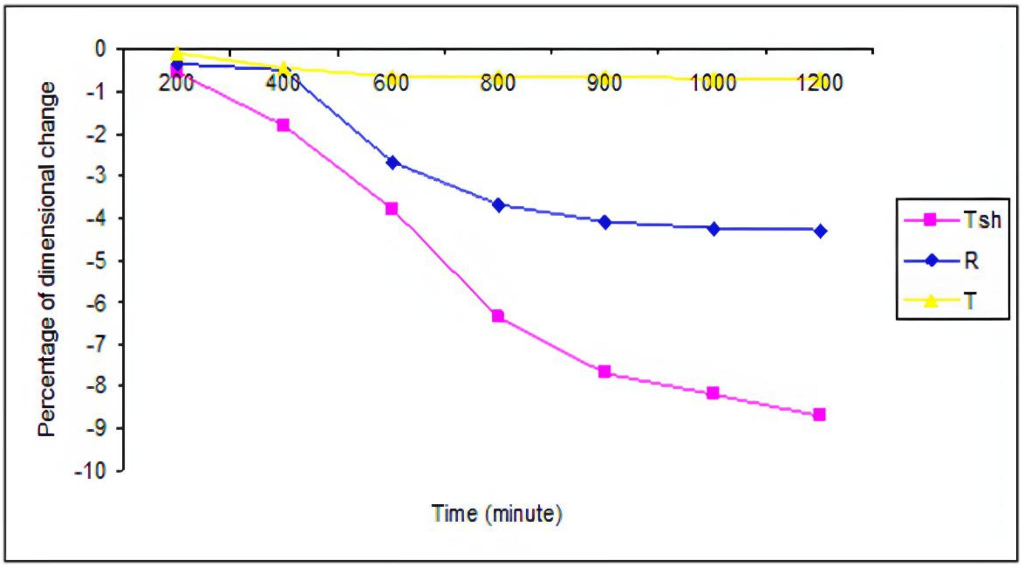


Figure 7: The percentage of shrinkage over time according to the experimental direction at β = 0.0°.

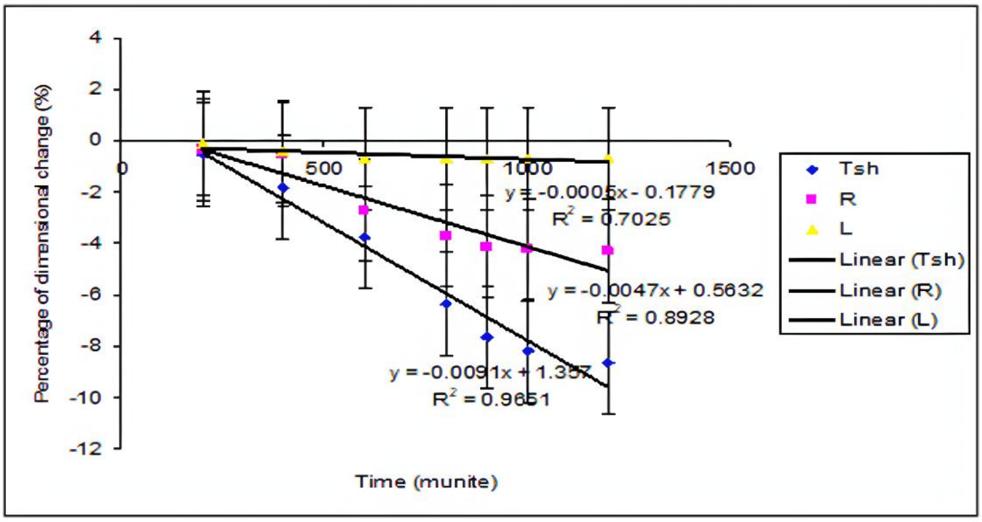
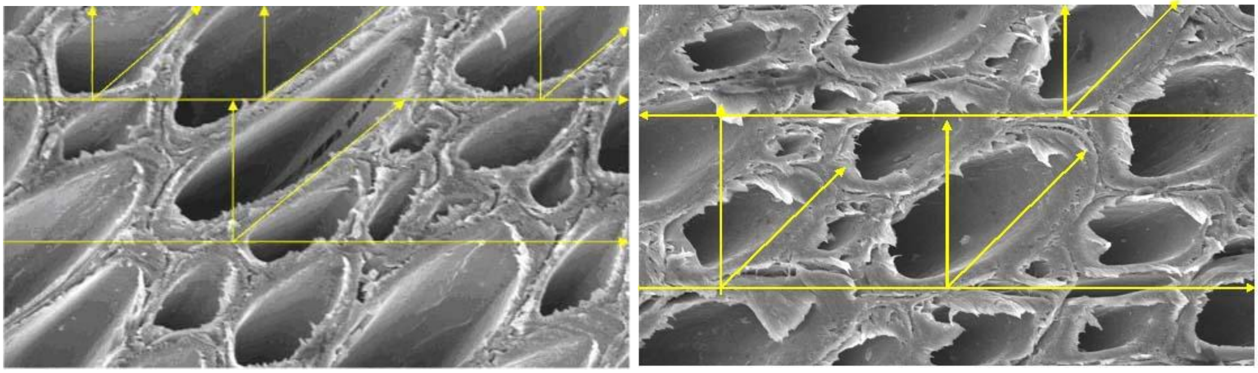
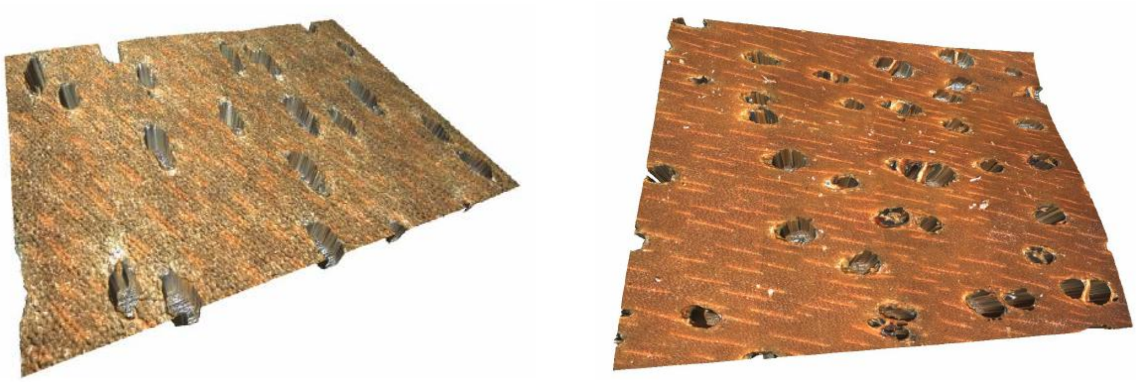


Figure 8: The error bar of the percentage of shrinkage over time for angle, β = 0.0°.



(a) (b)

Figure 9: SEM micrograph, X 2000, scale bar =20 µm, showing the lumen cell wall and the fibre orientation of *A. mangium* wood at β = 45.0° (a) before oven-drying. (b) after drying for 20 hours under temperature 105 C°. Note, a slight change in lumen size and the thickness of the cell wall.



(a) (b)

Figure 10: (a) The 3D module wood at 10.0 mm from the pith centre. (b) module wood at 40.0 mm from the pith center at β = 45.0°.

Table 5: The variation of percentage of tangential, radial and longitudinal swelling and shrinkage with the grain angle β.

Grain orientation angle β (°)	Tangential Swelling (%)	Redial Swelling (%)	Longitudinal Swelling (%)	Tangential Shrinkage (%)	Redial Shrinkage (%)	Longitudinal Shrinkage (%)
0.0	6.478	4.289	0.69	8.663	4.278	0.69
20.0	5.657	3.861	1.573	7.593	4.138	1.642
30.0	4.892	3.520	2.239	7.210	3.948	2.015
40.0	3.795	2.320	2.935	4.860	2.863	2.730
45.0	2.545	1.894	3.937	2.758	2.385	3.105
50.0	2.146	1.456	4.041	2.351	2.257	3.361

90.0	1.793	1.240	4.256	2.510	2.107	3.738

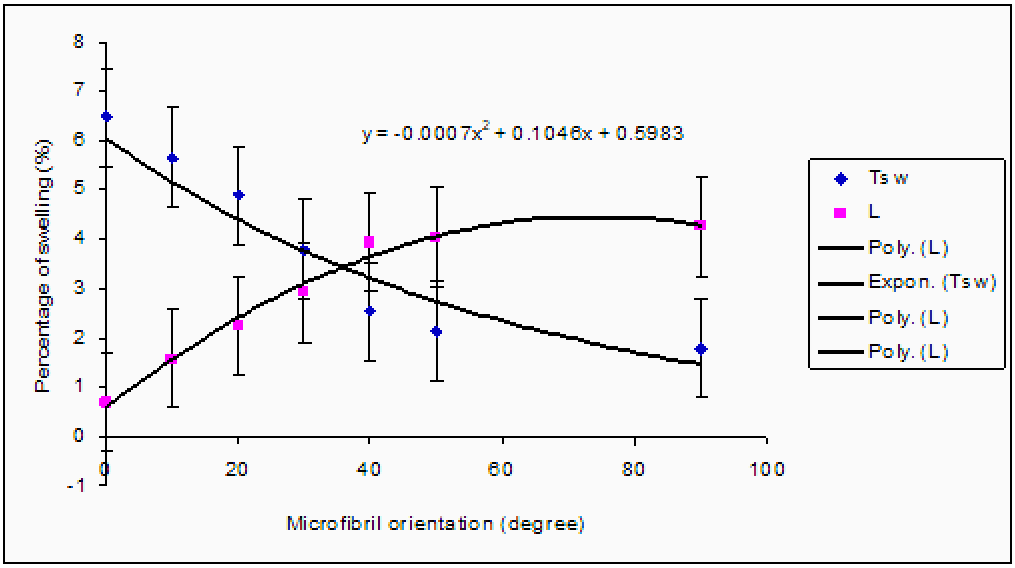


Figure 11: The relationship between Tangential, Longitudinal swelling and grain orientation in *A. mangium* wood at age 15-year-old.

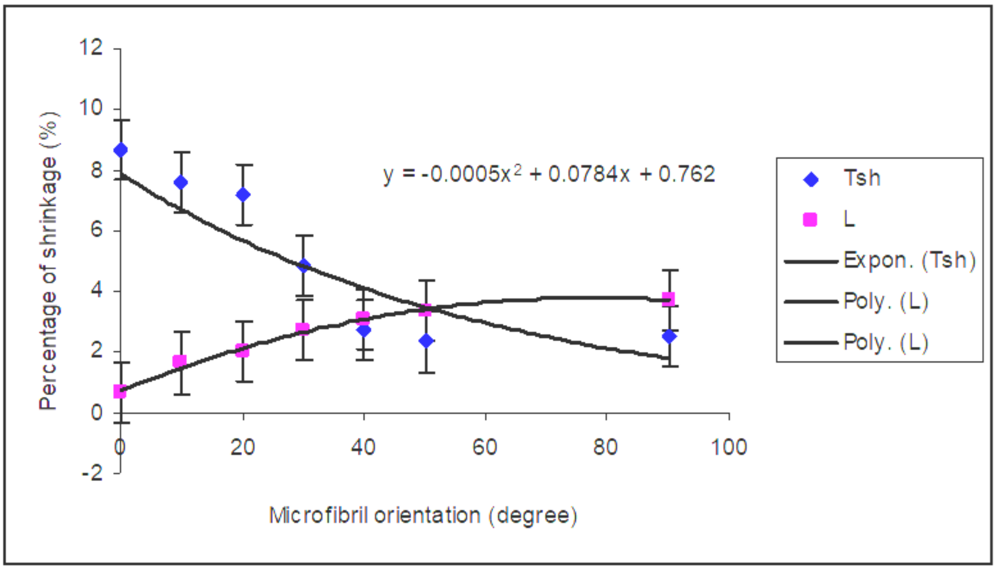


Figure 12: The relationship between Tangential, Longitudinal shrinkage and grain orientation in *A. mangium* wood at age 15-year-old.

Table 6: The variation of volumetric swelling and shrinkage with angle β for wood model at 15-year-old.

Sample No.	**Orientation angle, β (°)**	**α_v (%)**	**β_v (%)**
1	0.0	11.734	13.594
2	20.0	11.309	13.059
3	30.0	10.823	12.889
4	40.0	9.138	10.314
5	45.0	8.424	8.183
6	50.0	7.766	7.916
7	90.0	7.311	8.302

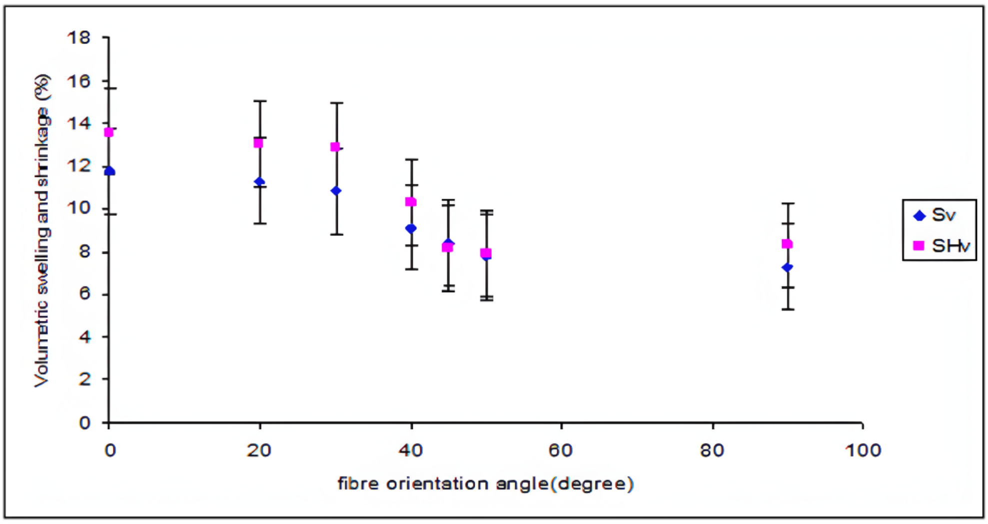


Figure 13: The variation of volumetric swelling and shrinkage with fibre orientation angle in *A. mangium* wood at age 15-year-old.

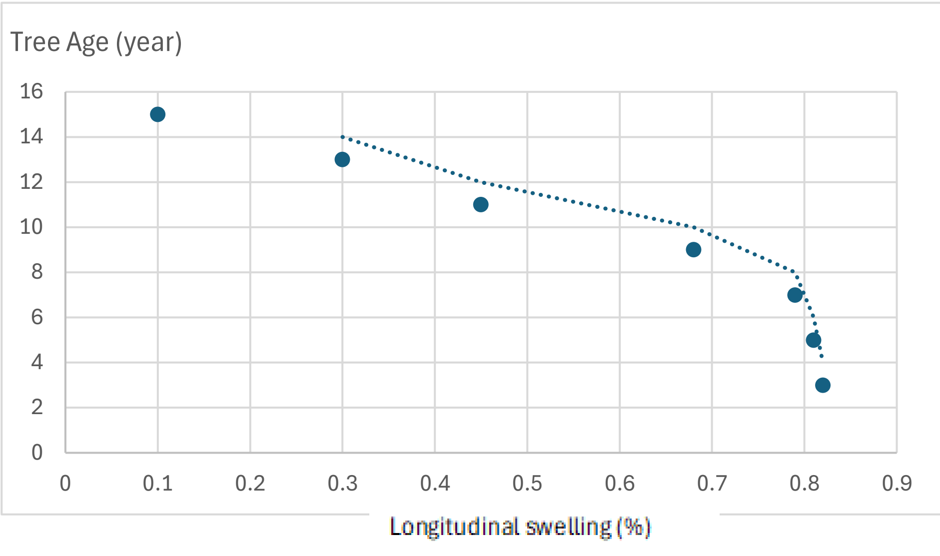


Figure 14: The variation of longitudinal swelling with tree age of *A. mangium* wood.

4 Discussion

Acacia mangium was found to shrink in length while simultaneously exhibiting less shrinkage in the tangential and radial directions at an angle of β = 45.0°. The percentage of tangential, radial and longitudinal swelling and shrinkage at angle β = 0.0° was studied. Using the same formula, we calculated the percentages of tangential, radial, and longitudinal swelling and shrinkage at angles β = 20.0°, 30.0°, 40.0°, 45.0°, 50.0°, and 90.0°, derived from 9-year-old *A. mangium* wood. The curves' shapes as swelling and shrinkage take place throughout the first ten hours are seen in Figures 5, 6, and 7. The tangential swelling is always greater than the radial (Table 2). The longitudinal swelling and shrinkage are considered negligible at grain angle β = 0.0° (Table 3). If the fiber orientation in the cell wall makes an angle of 90°, longitudinal shrinkage and swelling were found to increase whilst tangential and radial shrinkage or swelling decrease. At β = 45°, this results in the occurrence of longitudinal shrinking and swelling, accompanied by a corresponding reduction in tangential and radial shrinking and swelling. Tangential swelling was found to increase from 0.189% to 2.545%, and radial swelling increased from 0.09% to 1.894%, while those for longitudinal swelling increased from 1.575% to 3.937% at angle β =45.0° ± 0.5°. The percentage of shrinkage of *A. mangium* wood in the tangential direction was also found to increase from 0.10% to 2.758%, and radial shrinkage increases from 0.095% to 2.385%. The longitudinal shrinkage increased markedly from 1.548% to 3.105%. The results indicated that varying the grain angle from β = 20.0° to the point where the fibre is orientated perpendicular to the long axis of the cell wall at β = 90.0° progressively reduced both tangential and radial swelling and shrinkage. The findings also demonstrated that at angles between β = 45.0° and β = 90.0°, longitudinal swelling and shrinkage were substantially greater than tangential and radial. At grain angle β = 90.0°, a significant correlation was found between the longitudinal shrinkage and the percentage of dimensional change (R^2 = 0.98). There was no significant correlation (R^2 = 0.50) between the longitudinal swelling time and the dimensional change, while a relationship (R^2 = 0.66) was found between the percentage of tangential and radial swelling over time at angle β = 0.0° (Figure 6). Figure 7 shows the percentage of tangential, radial and longitudinal shrinkage over time at angle β = 0.0°.

Figure 9 (a) shows the SEM image for the lumen cell wall and the grain orientation of the wood sample at β = 45.0° before drying, while Figure 10 (b) shows the SEM micrograph for the sample at β = 45.0° after drying for 20 hours at a temperature of 105 C°. The grain angle in the wood sample could influence the shrinkage pattern. A larger angle in the longitudinal direction might contribute to the increased shrinkage in length. Moreover, the arrangement and structure of cellulose, hemicellulose, and lignin in the cell wall might be affecting shrinkage. Lignin, being more isotropic, could be contributing to reduced shrinkage in the tangential and radial directions (Alvin Muhammad Savero et al., 2022). The study deduced that non-uniform moisture distribution within *A. mangium* wood could lead to differential shrinkage. If the wood dried faster in the longitudinal direction, it might shrink more in length.

It was found that the lumen size varies slightly during drying compared to its size before drying because, after the oven's drying, the fiber in the cell wall will shrink on the inner side. Tangential swelling and shrinkage were 6.478% and 8.663% respectively (5). *A. mangium* wood swells and shrinks longitudinally at β = 90.0°, the maximum percentage of longitudinal swelling and shrinkage were 4.256% and 3.738% respectively.

5 Conclusion

Results show that *A. mangium* wood of 15-year-old swells and shrinks in length but at the same time swells and shrinks less in the tangential and radial directions. It was found that swelling and shrinkage along the grain can be a major problem in *A. mangium* wood, even when the percentage of the swelling and shrinkage is small. The actual water uptake inside the vessels and through the fibres composite ranges from 4.445% to 6.981% after 20 hours drying under 105 C° ±1C°. It was concluded that the variations of water uptake inside all the wood discs were taken from. Overall, *A. mangium* wood swells in both radial and tangential directions, indicating that a linear relationship can be established with increasing water content over time, as demonstrated in Figure 6. Subsequently, the radial expansion becomes slightly uneven. *A. mangium* wood's anisotropic shrinkage and swelling behavior should be considered when designing and constructing structures to ensure durability and longevity. The findings can inform the development of more effective wood treatment processes to enhance stability and performance. Finally, results also indicate that younger trees tend to have a higher proportion of juvenile wood, which exhibits greater swelling and shrinkage compared to old wood. As trees age, the proportion of heartwood increases, which is often denser and less susceptible to swelling and shrinkage than sapwood.

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Conflict of interest
The authors declare no conflict of interest

Authors' contribution
TAT: Conceived of the presented idea. Developed the theory and performed the computations Writing- Original draft preparation and verified the analytical methods. **AH:** Writing – review and editing. **NMA:** Discussed the results and contributed to the final manuscript.

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