



Effects of Solvent Soaking and Oven Drying on the Properties of Oil Palm Wood: A Single-Trunk Proof-of-Concept Study

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ABSTRACT. Oil palm wood (OPW) is an abundant lignocellulosic resource, but its utilisation is constrained by high and uneven moisture content and substantial radial heterogeneity. This proof-of-concept study evaluated the effects of soaking in ethanol, acetone, or toluene for 24 h before oven drying at 80 °C. Specimens were obtained from the inner and outer radial zones of the lower stem of a single 25-year-old oil palm trunk. Moisture content, density, volumetric shrinkage, microstructure, and bending properties were evaluated, with six specimens per treatment and radial layer for each measured property. Treatment and layer effects were assessed using two-way analysis of variance, followed by Tukey's HSD test. Ethanol was the only solvent that significantly reduced moisture content relative to the untreated control, from $148.86 \pm 7.99\%$ to $60.57 \pm 2.81\%$ in the inner layer and from $64.96 \pm 5.89\%$ to $38.09 \pm 1.80\%$ in the outer layer. Acetone produced the highest outer-layer volumetric shrinkage ($6.36 \pm 0.64\%$), significantly exceeding that of ethanol and toluene but not the untreated control. Bending responses varied between radial layers. Acetone produced the highest outer-layer modulus of rupture (25.99 N/mm^2) and modulus of elasticity (4972.84 N/mm^2), whereas toluene produced the highest inner-layer modulus of elasticity (749.81 N/mm^2). Scanning electron microscopy revealed treatment-dependent changes in vascular bundles and parenchymatous tissue. Exploratory pooled correlations indicated negative associations of moisture content and positive associations of density with bending properties. These findings indicate that solvent responses depend on the property and radial layer. As all specimens originated from one trunk, validation using independent trunks is required before broader recommendations can be made.

Keywords: *Oil palm wood, Organic-solvent pretreatment, Moisture content, Radial variation, Mechanical properties, Scanning electron microscopy*

1. INTRODUCTION

Oil palm plantations generate substantial quantities of lignocellulosic biomass during replanting, and the oil palm trunk (OPT) is one of the largest components of this residue stream (Ching et al., 2019; Terry et al., 2021). Converting OPT into oil palm wood (OPW) offers an opportunity to improve biomass utilization and reduce dependence on conventional timber resources. OPW has been considered for panels, furniture, composites, and light construction, although its variable quality continues to restrict wider use (Rosli et al., 2016; Srivaro et al., 2019). Retention and poor management of felled biomass may also create phytosanitary concerns in plantations, including disease pressure associated with *Ganoderma boninense* (Sahebi et al., 2017). The main processing difficulty is the heterogeneous anatomy of the oil palm stem. Unlike conventional hardwoods, OPT does not undergo secondary

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thickening and consists of vascular bundles embedded in parenchymatous ground tissue. The distribution of these tissues varies radially, producing a denser outer zone and a softer, more porous inner zone (Abe et al., 2013; Ahmad et al., 2018; Srivaro et al., 2018).

Moisture content also varies markedly across the stem, generally increasing toward the central region where parenchymatous tissue is more abundant (Wulandari & Erwinsyah, 2020). The density and distribution of vascular bundles are closely related to mechanical response, making radial position an important factor when evaluating OPW performance (Choowang, 2018). Drying is therefore a critical step in OPW processing. Conventional drying can lead to collapse, checking, warping, and other dimensional defects when moisture is removed unevenly from a material with large anatomical and density gradients. Previous work has explored kiln, forced air, and accelerated drying approaches, but maintaining dimensional stability and mechanical performance remains difficult (Anis et al., 2020; Nadzim et al., 2021; Rais et al., 2021). Pretreatment before final drying may provide an additional means of modifying moisture transport and reducing some of these limitations. Organic solvents differ in polarity, affinity for water, and interaction with wood constituents. Ethanol has previously been investigated for reducing drying defects and shrinkage in OPT (Azura et al., 2018; Othman et al., 2023), while hydrogen-bonding interactions between ethanol and water provide a physicochemical basis for its strong association with moisture (Finneran et al., 2015). However, direct comparison of ethanol, acetone, and toluene within the same OPW experiment, while explicitly considering inner and outer radial zones, remains limited.

The present study therefore compared these three solvent pretreatments, applied as soaking followed by oven drying, and evaluated their effects on moisture content, volumetric shrinkage, density, microstructure, and bending performance of radially segregated OPW in a single-trunk, proof-of-concept experiment.

2. METHODOLOGY

2.1. Raw material and specimen preparation

The experimental material was obtained from a 25-year-old oil palm trunk sourced from Pusat Penyelidikan Pertanian Tun Razak (PPPTR), Jerantut, Pahang, Malaysia. Only the lower portion of the trunk, extending from breast height to approximately 3 m along the stem, was used. The trunk was segregated radially into an inner zone comprising the 60% of the cross section nearest the pith and an outer zone comprising the remaining 40%. This segregation was used to account for the strong radial variation in OPW anatomy and properties (Bakar et al., 2022). Specimens were cut to the dimensions required by the respective ASTM and BS ISO test methods. Six specimens were prepared per treatment layer combination for each property (Table 1). All specimens originated from a single trunk and were randomly allocated to treatments within each radial zone. They are therefore subsamples of one trunk and not independent biological replicates; the experiment tests treatment differences within this trunk only, and between tree variation was not assessed.

Table 1. Test methods and specimen dimensions used in the study.

Property	Standard	Specimen size (mm)	n
Density	ASTM D2395-17	20 × 20 × 60	6
Moisture content	ASTM D4442-20	20 × 20 × 20	6
Volumetric shrinkage	ASTM D4933-16	20 × 20 × 100	6
Bending	BS ISO 13061-4:2014	20 × 20 × 300	6

2.2. Organic-solvent pretreatment and drying

Four groups were evaluated within each radial zone: untreated control, toluene, ethanol, and acetone. For each solvent treatment, specimens were fully immersed for 24 h at room temperature (approximately 25°C) in tightly sealed containers containing 500 mL of solvent, with the specimens wrapped in plastic to minimize evaporation. After soaking, specimens were removed, allowed to drain for 15 min, and gently blotted to remove surface solvent. Treated specimens were then dried in a Memmert Universal Oven UN110 at 80°C for 24 h until a target moisture content of constant mass. The same schedule was applied to all treatments and layers and to the untreated controls. Specimens were subsequently conditioned at $20 \pm 3^\circ\text{C}$ and $65 \pm 2\%$ relative humidity before testing. Mass loss was not recorded during drying; consequently, this study evaluates the combined effect of solvent soaking and oven drying on final properties and does not assess drying rate or drying time.

2.3. Physical and mechanical testing

Density was determined according to ASTM D2395-17 from measured mass and specimen volume. Moisture content was measured according to ASTM D4442-20: specimens were oven dried at $103 \pm 2^\circ\text{C}$ to constant mass, and moisture content was calculated on an oven dry mass basis. Moisture content was determined after oven drying and conditioning. Linear shrinkage in the radial, tangential, and longitudinal directions was determined according to ASTM D4933-16 from specimen dimensions before and after oven drying at $103 \pm 2^\circ\text{C}$, and volumetric shrinkage was calculated for each specimen as $100 \times [1 - (1 - \epsilon_R)(1 - \epsilon_T)(1 - \epsilon_L)]$, where ϵ_R , ϵ_T , and ϵ_L are the radial, tangential, and longitudinal shrinkage fractions. Static bending tests were performed using a universal testing machine with Instron software at a loading rate of 10 mm/min, and modulus of rupture (MOR) and modulus of elasticity (MOE) were calculated from the load deflection response in accordance with BS ISO 13061-4:2014.

2.4. Scanning electron microscopy and data analysis

Cross sectional specimens from untreated and solvent treated OPW were examined using scanning electron microscopy (SEM) to compare vascular bundles and parenchymatous tissue. Sections measuring approximately 1.0×1.0 cm were gold-coated using a Polaron SC 515 ion sputter coater and examined with a LEO Supra 50 VP scanning electron microscope. The comparative micrographs used in this study were evaluated qualitatively at approximately 80× magnification. Data are presented as mean of six specimens per treatment layer combination. Effects of treatment, layer, and their interaction were tested by two-way analysis of variance (ANOVA), and

treatments were compared within each layer by Tukey's honest significant difference test ($\alpha = 0.05$). Because all specimens were taken from one trunk, the p-values describe treatment differences within this trunk and do not support inference to the OPW population. Pearson product moment correlation was used to examine the pooled relationships of moisture content and density with MOR and MOE across all layers and treatments ($n = 48$ observations).

3. RESULTS AND DISCUSSION

3.1. Physical properties

Untreated OPW showed a clear radial contrast in physical properties (Table 2). The inner layer had a lower density (226.81 kg/m^3) and a higher moisture content (148.86%) than the outer layer (272.68 kg/m^3 and 64.96% , respectively). This pattern is consistent with the greater abundance of moisture holding parenchymatous tissue toward the central region of the trunk and the higher concentration of vascular bundles in the denser outer zone (Srivaro et al., 2018; Wulandari & Erwinsyah, 2020). Treatment, layer, and their interaction significantly affected moisture content ($p < 0.001$). Ethanol was the only solvent that reduced moisture content relative to untreated OPW in both radial zones (inner layer: 60.57% ; outer layer: 38.09% ; $p < 0.001$). This strong response is consistent with earlier OPT studies in which ethanol pretreatment affected drying behavior and shrinkage (Azura et al., 2018; Othman et al., 2023). Toluene did not change outer layer moisture content (65.27% vs. 64.96% for untreated OPW; $p = 0.999$) and did not significantly reduce inner layer moisture content (136.13%). Acetone lowered the mean outer layer moisture content to 58.96% , but the difference from untreated OPW was not significant ($p = 0.088$), and inner layer values (135.38%) did not differ from untreated OPW. The limited effect of toluene is consistent with its non-polar character and near immiscibility with water, whereas ethanol and acetone are miscible with water. Volumetric shrinkage was affected by treatment ($p < 0.001$) and layer ($p < 0.001$), whereas the treatment $\times$ layer interaction was not significant ($p = 0.095$). Inner layer shrinkage ranged from 2.94% (untreated) to 4.01% (acetone), with no significant differences among treatments. In the outer layer, acetone treated specimens showed the highest shrinkage (6.36%), which exceeded that of ethanol treated (4.72% ; $p = 0.013$) and toluene treated specimens (4.30% ; $p = 0.002$) but not that of untreated specimens (5.07% ; $p = 0.061$). Acetone therefore tended to increase dimensional change in the denser outer zone, whereas ethanol and toluene did not increase shrinkage relative to untreated OPW. All three solvent treatments reduced measured bulk density relative to the corresponding untreated layer. Consequently, the localized compaction observed in SEM images should not be interpreted as an increase in bulk density; cellular collapse or rearrangement can occur locally even when overall specimen density declines.

Table 2. Physical properties of untreated and solvent treated OPW ($n = 6$).

Treatment	Layer	Density (kg/m^3)	Moisture content (%)	Volumetric shrinkage (%)
Untreated	Inner	226.81	148.86 ^a	2.94 ^a
Untreated	Outer	272.68	64.96 ^a	5.07 ^{ab}
Toluene	Inner	200.75	136.13 ^a	3.37 ^a

Toluene	Outer	262.47	65.27 ^a	4.30 ^b
Ethanol	Inner	205.23	60.57 ^b	3.55 ^a
Ethanol	Outer	254.12	38.09 ^b	4.72 ^b
Acetone	Inner	193.27	135.38 ^a	4.01 ^a
Acetone	Outer	261.21	58.96 ^a	6.36 ^a

Note: Within each radial layer and property, means sharing a letter are not significantly different according to Tukey's HSD test ($p > 0.05$)

3.2. Microstructural response

The SEM micrographs showed distinct inner and outer layer morphologies and treatment dependent changes in the vascular bundles and surrounding parenchymatous tissue (Figure 1). Untreated inner OPW displayed a more open, porous matrix, whereas the untreated outer zone showed more closely packed structural tissue. These observations are consistent with the established radial variation in vascular bundle distribution and parenchymatous tissue in OPT (Abe et al., 2013; Wulandari & Erwinsyah, 2020). Toluene treated sections retained much of the original cellular appearance. Ethanol treated sections showed moderate alterations in the parenchymatous matrix and vascular bundle surroundings. Acetone treated specimens showed the most evident localized cell wall collapse and compaction, particularly around the parenchymatous tissue. Because the SEM assessment was qualitative, these images are best interpreted as morphological evidence of treatment response rather than as a quantitative measure of densification. This distinction is important because bulk density decreased after solvent treatment even where localized structural compaction was visible.

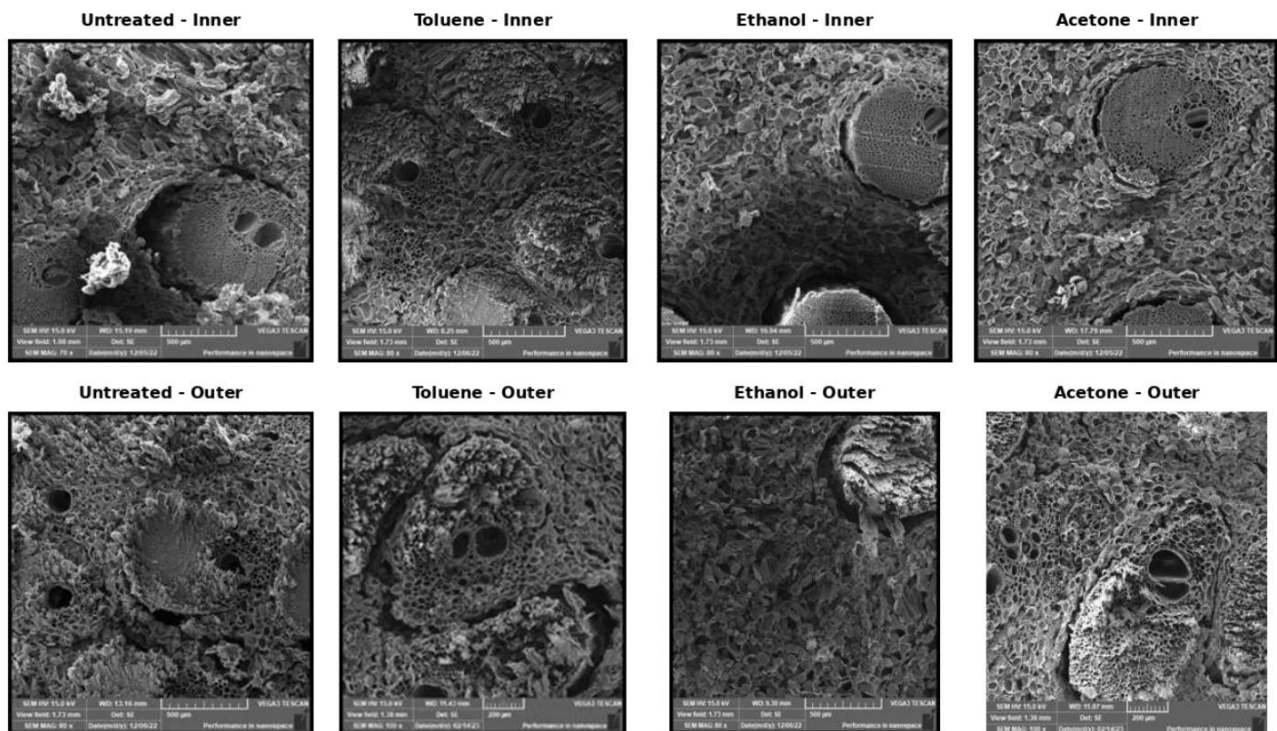


Figure 1. SEM cross-sections of untreated, toluene-treated, ethanol-treated, and acetone-treated OPW from the inner and outer radial zones.

3.3. Bending properties

Static bending properties were strongly layer dependent (Table 3). Treatment, layer, and their interaction significantly affected both MOR and MOE ($p < 0.001$). The radial contrast was clear. The untreated inner and outer MOR values were 3.20 and 3.90 N/mm². Solvent pretreatment produced only modest changes in inner layer MOR, with acetone reaching 4.21 N/mm². By contrast, outer layer MOR increased to 25.76 N/mm² with toluene, 24.79 N/mm² with ethanol, and 25.99 N/mm² with acetone. A similar pattern occurred for MOE. Toluene produced the highest inner-layer MOE (749.81 N/mm²), whereas acetone produced the highest outer-layer MOE (4972.84 N/mm²). Ethanol was most effective in reducing moisture content, while the highest bending-property values depended on the solvent and radial layer. These findings indicate that ethanol was most effective for moisture reduction, acetone produced the highest outer layer MOR and MOE, and toluene produced the highest inner layer MOE. The strong radial contrast is consistent with the influence of vascular bundle distribution and density on OPW mechanical behavior (Choowang, 2018; Srivaro et al., 2018). For practical processing, the choice of pretreatment should therefore be linked to the targeted property and the radial zone of the material rather than to a universal designation of one solvent as optimal.

Table 3. Bending properties of untreated and solvent-treated OPW (n = 6).

Treatment	Layer	MOR (N/mm ²)	MOE (N/mm ²)
Untreated	Inner	3.20	327.70
Untreated	Outer	3.90	344.40
Toluene	Inner	4.04	749.81
Toluene	Outer	25.76	4885.48
Ethanol	Inner	3.92	497.80
Ethanol	Outer	24.79	4488.72
Acetone	Inner	4.21	475.08
Acetone	Outer	25.99	4972.84

Note: Within each radial layer and property, means sharing a letter are not significantly different according to Tukey's HSD test ($p > 0.05$)

3.4. Relationships among moisture content, density, and bending properties

Pooled across layers and treatments (n = 48), moisture content was negatively correlated with MOE ($r = -0.614$, $p < 0.001$) and MOR ($r = -0.633$, $p < 0.001$), while density was positively correlated with MOE ($r = 0.611$, $p < 0.001$) and MOR ($r = 0.631$, $p < 0.001$) (Table 4). These coefficients are driven largely by the contrast between the inner and outer layers, in which the denser, drier outer zone also had higher MOR and MOE. Table 2 shows that measured density was lower after all solvent treatments. The results therefore indicate that treatment chemistry, radial anatomy, moisture removal, and local microstructural change act together rather than through density alone.

Table 4. Pearson correlations of moisture content and density with bending properties (pooled across layers and treatments, n = 48).

Predictor	MOE, r	p	MOR, r	p
Moisture content	-0.614	<0.001	-0.633	<0.001
Density	0.611	<0.001	0.631	<0.001

3.5. Study implications and limitations

The combined physical, microstructural, and mechanical results show that radial heterogeneity is central to the response of OPW to solvent pretreatment. The outer layer displayed much higher bending properties after treatment, together with a tendency toward greater shrinkage with acetone, whereas the inner layer showed greater moisture retention and more moderate changes in bending performance. Several limitations apply. All specimens came from one trunk, so treatment effects are confounded within trunk variation and cannot be extrapolated to other trees, sites, or ages; the study is a proof of concept. Further work should include at least three to five independent trunks, drying curves (mass loss versus time), longer-term durability testing, solvent recovery and safety assessment, and scale-up evaluation before industrial application.

4. CONCLUSION

In this single trunk, proof of concept study, soaking in organic solvents before oven drying at 80°C changed moisture content, microstructure, and selected engineering properties of OPW in a layer dependent manner. Ethanol was the only solvent that significantly lowered moisture content, in both the inner and outer zones. Acetone produced the highest outer layer volumetric shrinkage, which exceeded that of ethanol and toluene, and the highest outer layer MOR and MOE, while toluene produced the highest inner layer MOE. SEM observations showed treatment dependent changes in vascular bundles and parenchymatous tissue, particularly localized collapse and compaction in acetone treated sections. Pooled correlations linked lower moisture content and higher density with greater bending performance, although solvent treatment itself reduced measured bulk density. The results indicate that the effect of each solvent depends on the property and radial zone, and they do not identify a universally superior solvent. Replication with multiple independent trunks, together with drying-curve measurements, is required before the treatment can be recommended for industrial OPW drying.

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AUTHOR CONTRIBUTIONS

A.F. Awang Othman conceived the study, conducted material preparation and experimental testing, analysed the data, and drafted the manuscript. M.F. Arshad and the co-authors contributed to supervision, provided technical guidance, and critically reviewed and revised the manuscript. All authors approved the final manuscript.

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DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

The authors used ChatGPT for grammar checking and paraphrasing. All outputs were reviewed and validated by the authors.

DATA AVAILABILITY

The data are available from the corresponding author upon reasonable request.

COMPETING INTEREST

The authors declare that there are no competing interests regarding the publication of this paper.

COMPLIANCE OF ETHICAL STANDARDS

Not applicable. This study did not involve human subjects or live animal testing.

SUPPLEMENTARY MATERIAL

Not applicable

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