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SEM-EDS Characterization of the Elemental Composition of Nano-SiO2 and Furfuryl Alcohol-Impregnated White Teak Wood Powder

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A B S T R A C T

This study characterizes the elemental composition of white teak wood powder impregnated with nano-silicon dioxide (nano-SiO2) and furfuryl alcohol (FA) using Scanning Electron Microscopy–Energy Dispersive X-ray Spectroscopy (SEM-EDS) data. A focused reanalysis compared untreated control powder with impregnated powder from white teak originating in Southeast Sulawesi, Indonesia. The impregnated sample was dominated by carbon (63.69 wt%) and oxygen (34.52 wt%), with silicon (1.54 wt%), potassium (0.11 wt%), and calcium (0.14 wt%) present as minor constituents. The corresponding atomic fractions were 70.50% C, 28.69% O, 0.73% Si, 0.04% K, and 0.05% Ca. Silicon and potassium were not detected in the control, which contained 63.76 wt% C, 36.13 wt% O, and 0.12 wt% Ca. The appearance of 1.54 wt% Si after treatment provides local evidence of a silicon-bearing deposit consistent with the incorporation of nano-SiO2 during impregnation. Nevertheless, EDS alone does not establish chemical phase identity, and results from a single analyzed area cannot be considered representative of the entire specimen. Replicated elemental mapping together with complementary XRD, FTIR, or XPS analyses are required to confirm the distribution and chemical form of the deposited silicon.

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INTRODUCTION

White teak wood is a lignocellulosic material with potential applications in building components and engineered products. As with wood in general, its performance is governed by its porous structure and the interaction between the hydroxyl groups of the cell wall constituents and water. Water entering the lumen and the cell wall affects moisture content, shrinkage, swelling, stiffness, and biological durability (Aswad et al., 2025; Thybring et al., 2022). Modification through impregnation has therefore been developed to fill voids or alter the chemical environment of the cell wall so that water absorption and dimensional change can be controlled.

A previous study on white teak wood from Southeast Sulawesi reported that nano-SiO2 and furfuryl alcohol (FA) treatment reduced moisture content and improved dimensional stability relative to untreated control wood (Aswad et al., 2025). However, the elemental composition of the impregnated wood powder has not previously been a primary focus. The objectives of this study are: (i) to describe the elemental composition of C, O, Si, K, and Ca in nano-SiO2–FA-impregnated white teak wood powder; (ii) to compare it descriptively with control wood powder; and (iii) to assess the strength of evidence and the limitations of SEM-EDS interpretation in establishing the success of nano-SiO2–FA impregnation. The scope of the study is limited to the available elemental composition data; accordingly, the conclusions are not intended to establish crystal structure, chemical bonding, or the three-dimensional distribution of the impregnated material.

THEORETICAL FRAMEWORK

The combination of furfuryl alcohol (FA) and nano-SiO2 is of particular interest because it merges an organic component capable of in-situ polymerization with a nano-sized inorganic filler. Dong et al. (2014) showed that FA–nano-SiO2 impregnation of poplar wood produces a wood–polymer nanocomposite and deposits silica-based material within the lumen and cell wall. Another study reported that vacuum pressure influences the depth and homogeneity of silica penetration; at higher vacuum pressures, more particles were found within the wood vascular system, and water uptake capacity decreased (Lemaire-Paul et al., 2023). Similar findings on fast-growing wood species show that nano-silica-based formulations can improve dimensional stability, density, hardness, or water resistance, although the magnitude of the effect depends on species, formulation, and processing conditions (Rahayu et al., 2021, 2022; Tao et al., 2024; Weng et al., 2023).

Elemental information is important for assessing whether the observed surface areas or powder fragments genuinely contain silicon following the impregnation process.

SEM provides morphological information at the micrometer scale, whereas EDS detects the characteristic X-rays generated by the interaction between the electron beam and the sample, and reports the results as weight percentage and atomic percentage (Newbury, 1998; Newbury & Ritchie, 2019).

METHODS

Materials and Data Source

The dataset originates from a study of white teak wood (Gmelina arborea) from Southeast Sulawesi, reported in the 2024 Final Grant Report and related publications (Aswad et al., 2025). The test groups consisted of untreated control wood and wood impregnated using a nano-SiO2–FA system. In the parent study, physical specimens measuring 2 × 2 × 2 cm were used for testing of the control and impregnated wood. The present article reuses the SEM-EDS output data for the control and impregnated wood powders as a focused analysis.

Impregnation Treatment and Powder Preparation

In general, the wood was conditioned and dried prior to treatment with a nano-SiO2–FA impregnation solution using a pressure- or vacuum-assisted process, followed by drying to promote retention and polymerization of the material within the wood structure (Aswad et al., 2025; Dong et al., 2014; Lemaire-Paul et al., 2023). After treatment, sections of the wood were prepared as powder for SEM-EDS observation. The source report does not specify the sieve size, conductive coating method, accelerating voltage, beam current, working distance, live time, or the number of analyzed areas. Accordingly, these parameters are neither reconstructed nor assumed in this article and must be supplemented from the laboratory records prior to submission.

SEM-EDS Characterization

Powder morphology was observed by SEM at a scale indicated as 10 micrometers in the source image. The EDS spectrum recorded the characteristic peaks of C, O, Si, K, and Ca. All elements were reported using K-series lines. The quantification output included apparent concentration, k-ratio, weight percent (wt%), wt% sigma uncertainty, atomic percent, and the software's standard labels. Standard labels such as C Vit, SiO2, KBr, and wollastonite were treated as instrument quantification references rather than as direct identification of chemical phases within the sample.

Data Analysis

Data were tabulated without altering the original values. Absolute differences were calculated as delta wt% = impregnated wt% − control wt%. Because the dataset provides only a single aggregate compositional result for each condition, without replication across areas or specimens, the analysis is limited to descriptive statistics. No hypothesis testing, confidence intervals, or statistical significance claims were performed.

The interpretation of silica presence is based on the appearance of the Si element in the impregnated sample and its absence in the control, compared against literature evidence using SEM-EDS to support the localization of silica-based material within wood (Dong et al., 2014; Lemaire-Paul et al., 2023).

RESULTS

Morphology of Impregnated Wood Powder

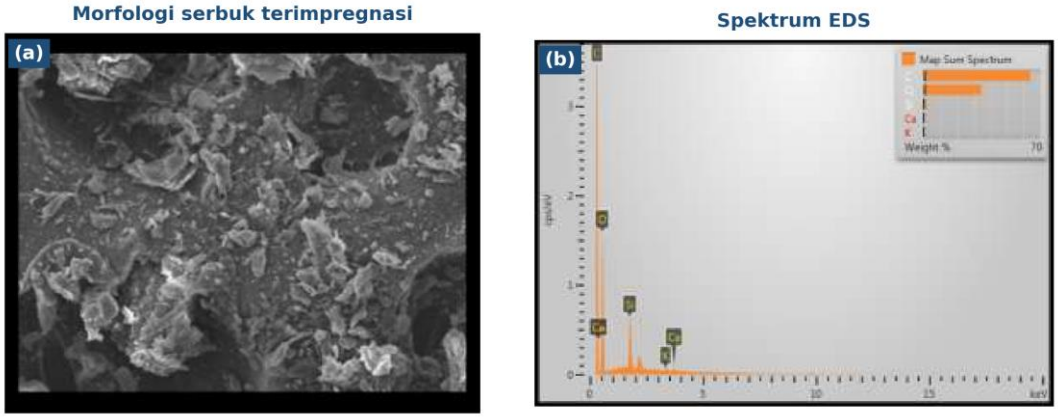

Figure 1. (a) SEM image of impregnated white teak wood powder at a scale of 10 micrometers, and (b) EDS spectrum showing the C, O, Si, K, and Ca peaks. Source: 2024 Final Grant Report.

The SEM image shows irregular fragment surfaces, with agglomerates and fiber fragments of various sizes. This morphology is consistent with a lignocellulosic powder material that has undergone drying, milling, and impregnation treatment. However, bright regions or agglomerates in the electron image should not be directly identified as SiO2 particles based on contrast alone, since brightness is also influenced by topography, surface orientation, charging, and effective atomic number. Morphological evidence must therefore be interpreted together with the spectrum and elemental mapping.

The spectrum in Figure 1(b) is dominated by the C and O peaks, as expected for the wood matrix and the organic FA component. A Si peak is evident at its characteristic energy and represents the main distinguishing feature relative to the control. The K and Ca peaks are of low intensity and are therefore categorized as trace elements within the analyzed area.

Elemental Composition of Impregnated Wood Powder

Table 1. EDS quantification output for impregnated wood powder

Element	Line	Apparent conc.	k-ratio	Wt%	Sigma	Atomic %	Standard
C	K-series	40.90	0.40905	63.69	0.50	70.50	C Vit
O	K-series	21.99	0.07400	34.52	0.49	28.69	SiO2

Si	K-series	2.75	0.02179	1.54	0.05	0.73	SiO2
K	K-series	0.20	0.00171	0.11	0.03	0.04	KBr
Ca	K-series	0.26	0.00229	0.14	0.03	0.05	Wollastonite
Total	**-**	**-**	**-**	**100.00**	**-**	**100.00**	**-**

Source: primary SEM-EDS data from the 2024 Final Grant Report. Decimal values are retained as reported.

Table 1 shows that C is the dominant element by mass (63.69 wt%) and by atomic count (70.50 atomic%), followed by O at 34.52 wt% and 28.69 atomic%. The dominance of these two elements is consistent with a lignocellulosic matrix and a furan-based organic component. Because FA itself contains C and O, the high combined content of these two elements cannot be directly separated into contributions from the wood and from the FA polymer based on EDS alone. Functional-group chemical analysis such as FTIR or XPS is required to distinguish changes in the carbon–oxygen bonding environment.

Si was measured at 1.54 wt%, or 0.73 atomic%. The atomic% value is lower than the wt% value because the relative atomic mass of Si is greater than that of C and O. The presence of Si is the most specific indicator of silica-based impregnation material within this dataset. Nevertheless, the phrase 'SiO2 detected' must be used with caution: EDS directly detects the elements Si and O, whereas establishing that both are present within an SiO2 phase requires local stoichiometric information or a phase-identification method.

K and Ca were present at only 0.11 and 0.14 wt%, respectively. These low concentrations may originate from natural wood minerals, residues from the process materials, preparation contamination, or local heterogeneity. Without a chemical blank and multi-area mapping, the functional role of K and Ca cannot be confirmed. They are therefore more appropriately reported as trace elements rather than directly attributed to any specific property enhancement.

Comparison with Control Wood Powder

Table 2. Comparison of EDS composition between control and impregnated wood powders

Element	Control Wt%	Impreg. Wt%	Delta Wt%	Control Atomic%	Impreg. Atomic%
C	63.76	63.69	-0.07	70.13	70.50
O	36.13	34.52	-1.61	29.83	28.69
Si	0.00	1.54	+1.54	0.00	0.73
K	0.00	0.11	+0.11	0.00	0.04
Ca	0.12	0.14	+0.02	0.04	0.05
Total	**100.00**	**100.00**	**-**	**100.00**	**100.00**

Note: Delta = impregnated value − control value; the comparison is descriptive because EDS area replication was not available.

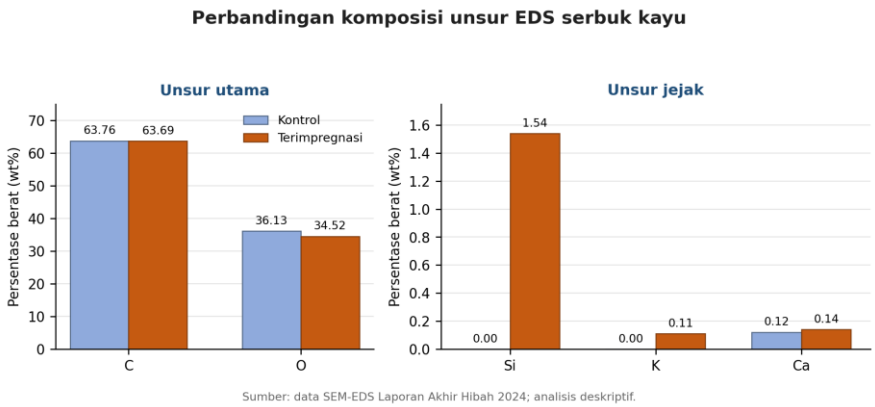

Figure 2. Comparison of the weight percentages of major and trace elements in control and impregnated wood powders.

The comparison in Table 2 and Figure 2 shows the clearest change in Si, from undetected in the control to 1.54 wt% after impregnation. In the context of this experiment, the appearance of Si is local evidence consistent with the deposition of nano-SiO2-based material. This result is in line with the study by Dong et al. (2014), who used SEM-EDS to demonstrate the incorporation of nano-SiO2 together with FA into the lumen and cell wall, as well as the study by Lemaire-Paul et al. (2023), who used EDS to assess the distribution of silica within the wood vascular system following vacuum treatment.

C remained relatively unchanged (−0.07 percentage points), whereas O decreased by 1.61 percentage points. Because the entire composition is normalized to 100%, an increase in the Si fraction mathematically reduces the relative fraction of the other elements. Consequently, the decrease in O should not be directly interpreted as the loss of oxygen-containing groups or an increase in hydrophobicity. Such a claim would require absolute measurements or spectroscopic analysis sensitive to chemical bonding.

The increase in Ca from 0.12 to 0.14 wt% is very small and falls within a range that may be sensitive to heterogeneity and quantification uncertainty. K appeared at 0.11 wt% in the treated sample but was absent in the control. Although the software reported a sigma of 0.03 wt% for K and Ca, this value does not substitute for point-to-point, area-to-area, or specimen-to-specimen variation. The discussion therefore does not treat the changes in K and Ca as statistically validated treatment effects.

DISCUSSION

Implications for Impregnation Success

Mechanistically, the vacuum or pressure process helps remove air from the lumen and opens pathways for the impregnation solution to enter. After pressure is restored, the solution moves into the cavities through pressure gradients and capillarity. FA can act as an organic phase that retains or carries nano-SiO2, subsequently polymerizing during heating (Dong et al., 2014; Augustina et al., 2023).

The appearance of Si in the impregnated powder indicates that at least some of the milled fragments contain silicon-based material, showing that the material is not present solely as a free liquid that is entirely lost upon drying.

However, the powder data do not directly indicate the depth of penetration within an intact wood block. Milling mixes material from both the surface and internal portions; without information on the sampling location of the powder, it cannot be determined whether the Si signal originates from the surface layer, the internal lumen, the cell wall, or loose agglomerates. To examine penetration, cross-sections from the surface toward the core would need to be mapped at several distances under identical acquisition conditions. This approach has been used in silica impregnation studies to distinguish surface deposition from diffusion into the vascular system (Lemaire-Paul et al., 2023).

The relationship between the presence of Si and the improvement of physical properties is plausible but not established as causal from EDS data alone. The parent study showed a decrease in average moisture content from approximately 0.16 in the control to 0.11 in the treated wood, together with improved dimensional stability (Aswad et al., 2025). Studies on other wood species have similarly reported filling of the lumen or cell wall by polymer–nano-silica systems accompanied by reduced water absorption and improved dimensional stability (Rahayu et al., 2021, 2022; Tao et al., 2024; Weng et al., 2023). Although consistent, the quantitative relationship in white teak wood requires further testing by correlating Si content across multiple specimens with WPG, water uptake, ASE, or volumetric change.

Reliability and Limitations of SEM-EDS

Modern EDS can provide reliable quantification of major, minor, and some trace elements when calibration, standards, matrix corrections, preparation, geometry, and acquisition conditions are properly controlled (Newbury & Ritchie, 2019). In contrast, standardless analysis can carry substantial relative error; Newbury (1998) reported that 95% of the results from some standardless procedures fall within approximately ±25% to ±50% relative error compared with more accurate standards-based results. Because the source report displays standard labels without clarifying whether quantification was genuinely standards-based or derived from a standardless library, the reported wt% values should be treated as semi-quantitative.

The principal limitation of the dataset is the absence of field-of-view replication, the number of analyzed points, instrument parameters, coating details, and the powder sampling location. If the sample was carbon-coated, the C value may be affected; if a particular holder or adhesive was used, additional elements may also be introduced. The rough topography of the powder further increases variation in take-off angle and X-ray absorption. Accordingly, the 100% total generated by the software reflects the normalization of the elements included in the model, rather than evidence that all chemical components of the sample have been fully measured.

CONCLUSIONS AND RECOMMENDATIONS

Nano-SiO2–FA-impregnated white teak wood powder was dominated by C at 63.69 wt% and O at 34.52 wt%, with the minor elements Si at 1.54 wt%, K at 0.11 wt%, and Ca at 0.14 wt%. The corresponding atomic composition was 70.50% C, 28.69% O, 0.73% Si, 0.04% K, and 0.05% Ca. Compared with the control, the principal change was the appearance of Si, from 0.00 to 1.54 wt%, while C remained relatively unchanged and O decreased by 1.61 percentage points.

The appearance of Si provides qualitative to semi-quantitative local evidence consistent with the incorporation or retention of nano-SiO2-based material following impregnation. However, the EDS results are insufficient to establish the SiO2 chemical phase, the homogeneity of its distribution, or a causal relationship with improved wood properties. Practically, these findings support the use of nano-SiO2–FA impregnation as a promising treatment for enhancing the dimensional stability of white teak wood, provided that the deposition is confirmed through the additional validation described below.

FURTHER STUDY

This study is limited to a single aggregate EDS measurement per condition without replication across specimens or analyzed fields, and several acquisition parameters (coating, accelerating voltage, working distance, live time) were not documented in the source report. Future work should therefore include a minimum of three specimens per condition, multiple EDS fields sampled from the surface toward the core, full documentation of instrument parameters and preparation blanks, and complementary characterization methods such as XRD, FTIR, or XPS to confirm the distribution and chemical form of the deposited silicon.

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