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Development of Protective Coating for Wooden Artifacts Using Organosilane Hydrophobicity

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We investigate the application of organosilane-based coatings as functional materials for the protective structural layer of wooden artifacts. To evaluate the protective efficacy, advanced sensing and characterization techniques—including colorimetry for color change analysis and the sessile drop method for optical contact angle measurement—were employed to perceive and quantify surface property variations. Organosilanes, specifically methyltrimethoxysilane (MTMS), can form stable Si–O–C bonds with cellulose through hydrolysis and condensation, creating a durable hydrophobic network within the wood. In this research, we compare the developed coating with polyethylene glycol (PEG) 2000, PEG 4000, and a commercial protective agent. Experimental results, quantified through these sensing instruments, demonstrate that the developed coating achieves high hydrophobicity with contact angles ranging from 90° to 120°, significantly outperforming the PEG-based groups. Furthermore, colorimetric sensing analysis indicates minimal color variation, with a total color difference (ΔE^*) as low as 0.68 for Taiwan red cypress, thereby preserving the visual integrity of the artifacts. The coating also exhibits the fastest drying time and superior stain and acid resistance. These findings suggest that integrating functional material development with sensing evaluation offers a scientifically sound and highly operable technique for the sustainable conservation of wooden cultural heritages.

1. Introduction

Wooden materials have been widely used in traditional Taiwanese architecture and heritage structures because of their excellent mechanical properties and rich cultural significance.[1–3] These components, found in beams, columns, and religious imagery in temples, serve as vital symbols of social authority and communal cohesion. However, extreme climatic conditions and moisture-induced erosion pose substantial threats, leading to structural degradation and surface paint peeling.[4,5] Traditional conservation methods, such as painting organic films, often lack long-term stability and breathability.[6–8] Therefore, the development of functional materials that enhance structural strength while maintaining material stability is a critical focus.

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Recent advancements in wood science have highlighted the potential of organosilane compounds for cultural relic restoration. Organosilanes can form durable bonds between organic and inorganic surfaces through a hydrolysis-condensation mechanism, creating a stable siloxane (Si–O–C) network within the wood cell walls.[9–11] Compared with traditional polymers, these modern silane treatments offer superior permeability and environmental friendliness. Despite their promise, a significant challenge remains in the precise, nondestructive evaluation of these protective layers once applied to diverse wood species.

To address this, the integration of sensing and characterization technologies is essential for quantifying protective efficacy.[12–14] In this study, we utilize optical sensing instruments—specifically, colorimetric sensors and sessile drop contact angle measurement—to perceive and monitor the surface property variations of treated wood. By employing these sensing evaluation methods, we investigate the reinforcement mechanisms of methyltrimethoxysilane (MTMS) on three characteristic Taiwan wood species: Taiwan red cypress (*Chamaecyparis formosensis*), Taiwan incense cedar (*Calocedrus formosana*), and Taiwan bull camphor (*C. kanehirae*).

The objective of this research is to evaluate the developed coating's performance against polyethylene glycol (PEG) and commercial agents. By bridging functional material development with sensing-based performance analysis, we aim to provide a scientifically sound and highly operable technique for the sustainable conservation of Taiwan's traditional architecture.

2. Materials and Methods

2.1 Experimental materials

The test specimens used in this study were selected from three wood species characteristic of traditional Taiwanese cultural heritage: Taiwan red cypress (*Chamaecyparis formosensis*), Taiwan incense cedar (*Calocedrus formosana*), and Taiwan bull camphor (*C. kanehirae*). These species were chosen for their prevalence in historic temples and religious artifacts. All wood samples were prepared into standardized dimensions of 60 × 60 × 30 mm^3 for consistent testing. MTMS was used as the primary organosilane agent, while PEG (PEG 2000 and PEG 4000) and a commercial protective agent (Rainbow Paint brand) served as control groups. The experimental procedure is shown in Fig. 1.

2.2 Preparation of functional protective coating

The reinforcing solution was prepared by measuring 50 mL of 3–5% MTMS solution into a glass beaker. To ensure optimal solvent diffusivity and surface wettability, ethanol and glycerol were added in a precise volume ratio of 10:1 (40 mL of ethanol and 4 mL of glycerol). The mixture was subjected to continuous homogenization using a magnetic stirrer at 500 revolutions per minute (RPM) for 30 min at room temperature to ensure uniform dispersion before application.

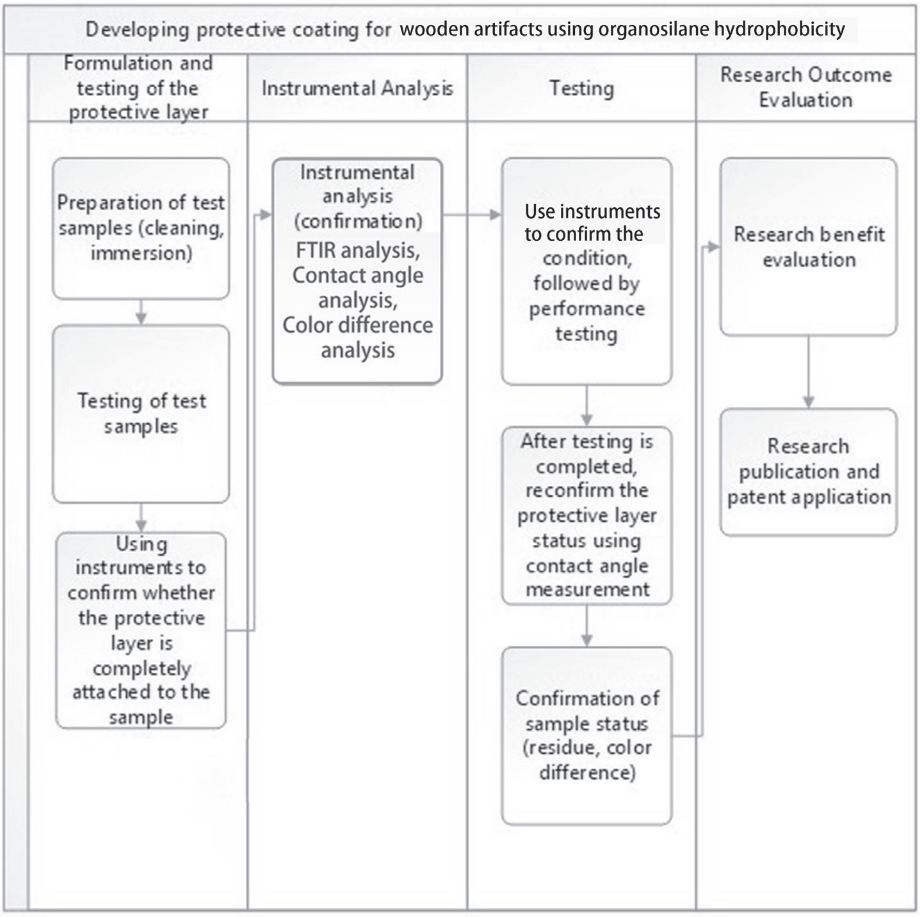


Fig. 1. Experimental procedure.

2.3 Sensing evaluation and surface characterization

To systematically assess the protective efficacy of the developed organosilane-based functional materials, we employed a multidimensional sensing evaluation approach. The characterization was focused on quantifying color stability, surface wettability, and chemical structural changes using high-precision optical and chemical sensors.

2.3.1 Preparation of reinforcing solution for reproducibility

To ensure the reproducibility of the functional coating, 50 mL of 3–5% MTMS solution was measured into a glass beaker. The solvent system was optimized with ethanol and glycerol in a precise volume ratio of 10:1 to enhance diffusivity. The mixture was subjected to continuous homogenization using a magnetic stirrer at 500 RPM for 30 min at room temperature to ensure uniform dispersion before the liquid impregnation of wood specimens.

2.3.2 Colorimetric sensing analysis

The visual integrity of the wooden artifacts was monitored using a colorimetric sensing system (Model SA5500). The instrument operated in reflectance mode as an optical sensor to quantify the L^*, a^*, and b^* values. The total color difference (ΔE^*ab) was calculated using the following sensing formula to perceive subtle surface variations: $\Delta E*ab^* = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2}$. This sensing approach provides a quantitative reference for assessing whether the protective treatment alters the original aesthetic of the cultural heritage materials.

2.3.3 Hydrophobicity sensing analysis

Surface wettability was quantified by the sessile drop method integrated with an automated optical contact angle sensor. This sensing technique perceives the interaction between the liquid phase and the modified wood surface. A fixed volume (5 μL) of deionized water was deposited onto the specimens. The sensing core, comprising a high-resolution camera and image analysis software, captured the droplet profile to determine the contact angle. For consistent performance benchmarking, the developed coating was compared against PEG 2000, PEG 4000, and a unified commercial benchmark, the Rainbow Paint brand.

2.3.4 Chemical and microscopic sensing [Fourier transform infrared (FTIR) spectroscopy and microscopy]

To sense the formation of stable Si–O–C bonds and confirm the attachment of the protective layer, FTIR spectroscopy and optical microscopy were employed. These instruments served as chemical sensors to monitor the hydrolysis–condensation reactions between MTMS and the wood cellulose hydroxyl groups.

3. Results and Discussion

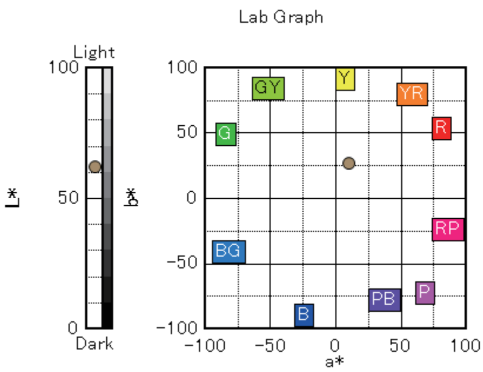
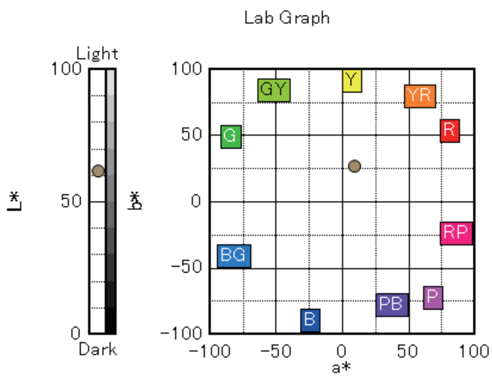
3.1 Colorimetric sensing analysis

To evaluate the impact of the functional coating on the visual integrity of wood, optical colorimetric sensing was conducted. The results (Table 1) indicate that the developed organosilane coating exhibited the highest color stability. Specifically, for Taiwan red cypress, the total color difference (ΔE^*) sensed was merely 0.68, and for *Calocedrus*, it was 1.04, both falling below the threshold of visual perception. In contrast, the PEG-based groups (2000 and 4000) showed significant color shifts, with ΔE values reaching 22.72 and 20.26, respectively. This sensing data confirms that the MTMS-based coating preserves the original aesthetic value of cultural artifacts far better than do traditional polymer treatments. The results are summarized in Tables 1 and 2.

Table 1
Results of colorimeter testing on wood samples.

Sample		Pre-treatment			Post-treatment			ΔE
		L^*	a^*	b^*	L^*	a^*	b^*	
Developed organosilane coating	Red cypress	62.11	10.03	27.26	61.85	9.4	27.22	0.68
	Calocedrus	43.11	12.98	17.57	42.11	13.09	17.83	1.04
	C. kanehirae	69.68	4.28	21.88	64.5	5.14	23.26	5.43
Rainbow Paint brand	Red cypress	63.56	9.8	24.69	58.18	10.96	24.79	5.50
	Calocedrus	50.58	11.1	19.9	50.58	11.69	22.27	2.44
	C. kanehirae	66.65	5.44	21.5	58.71	7.07	22.38	8.15
PEG 2000	Red cypress	55.7	12.88	26.46	42.4	16.92	22.99	14.33
	Calocedrus	45.75	9.63	17.07	40.93	9.67	16.63	4.84
	C. kanehirae	63.24	5.76	19.99	41.49	12.16	21.48	22.72
PEG 4000	Red cypress	65.08	9.01	25.09	46.89	16.76	29.53	20.26
	Calocedrus	45.93	8.99	14.32	45.5	8.12	11.53	2.95
	C. kanehirae	62.04	8.08	22.55	44.32	13.37	23.25	18.51

Table 2
(Color online) Results of color difference analysis.

Before coating-Taiwan red cypress	After coating-Taiwan red cypress
	
Uncoated	Coated

3.2 Evaluation of stain and acid resistance

The surface resistance to contaminants was evaluated using blue ink and diluted hydrochloric acid. The developed coating demonstrated excellent stain resistance and self-cleaning performance, with no visible residue observed after testing. Although the Rainbow Paint brand was initially labeled as “excellent” in Table 3, slight pigment residues were observed during the tests. To address this inconsistency, the evaluation criteria were refined to distinguish between “excellent” (no residue) and “acceptable” (slight residue). In the acid resistance test, all materials, including the MTMS coating and the Rainbow Paint brand, showed no bubbling or corrosion after exposure to diluted hydrochloric acid for 1–2 min, indicating stable protective performance against acidic contaminants.

Table 3
Stain resistance test results for wood samples.

No.	Red cypress	*Calocedrus*	*C. kanehirae*
Developed oligosilane coating	Excellent	Excellent	Excellent
Rainbow Paint brand	Excellent	Excellent	Excellent
PEG 2000 50%	Excellent	Excellent	Excellent
PEG 4000 50%	Excellent	Excellent	Excellent

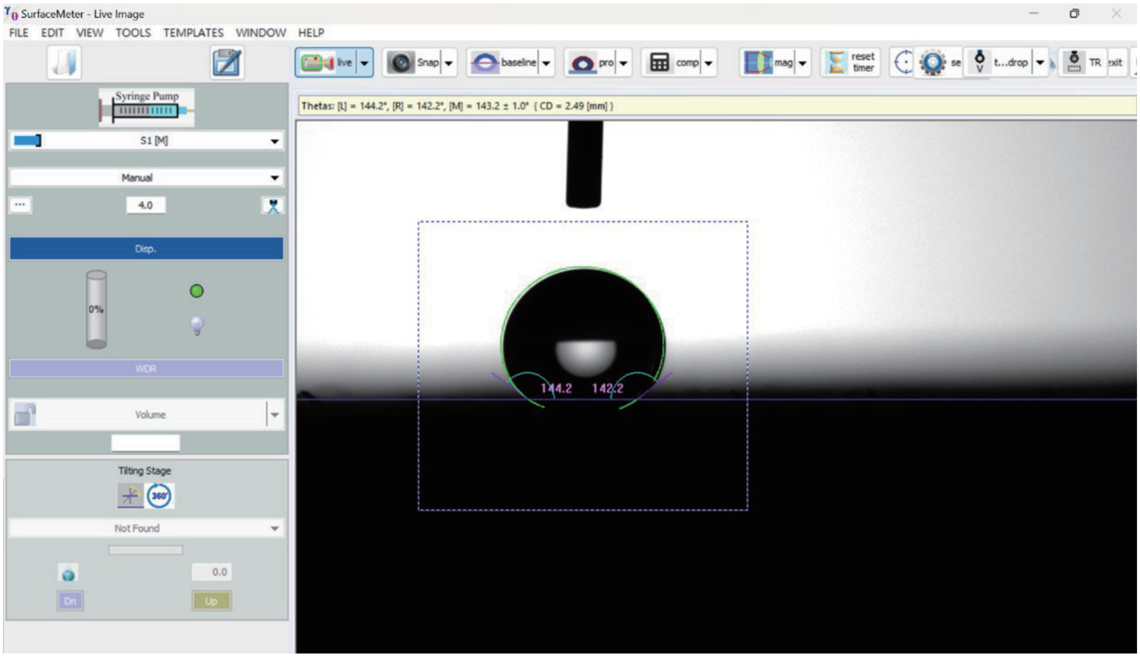


Fig. 2. (Color online) Results of contact angle analysis.

3.3 Hydrophobicity sensing and surface energy

The sessile drop sensing system provided critical data on surface wettability. The MTMS coating exhibited high contact angles for all tested species, ranging from 90° to 120°, as shown in Fig. 2, confirming stable hydrophobicity. The PEG groups exhibited contact angles between 15° and 35°, confirming their hydrophilic nature. The results are presented in Table 4.

3.4 Chemical bonding sensing (FTIR analysis)

To verify the reinforcement mechanism at the molecular level, FTIR spectroscopy served as a chemical sensor to monitor functional group variations. The sensing data confirms that during the hydrolysis and condensation process, the organosilanes react with the cellulose hydroxyl groups to form stable siloxane (Si–O–C) bonds. This molecular-level sensing confirms that the protective layer is not merely a surface film but is chemically integrated into the wood cell walls, providing durable consolidation and moisture resistance. The results are presented in Fig. 3.

Table 4
Results of contact angle analysis.

No.	Contact angle	Property
Developed oligosilane coating	90–120 degrees >120 degrees	Hydrophobic
Rainbow Paint brand	90–120 degrees >120 degrees	Hydrophobic
PEG 2000 50%	15–35 degrees	Hydrophilic
PEG 4000 50%	15–35 degrees	Hydrophilic

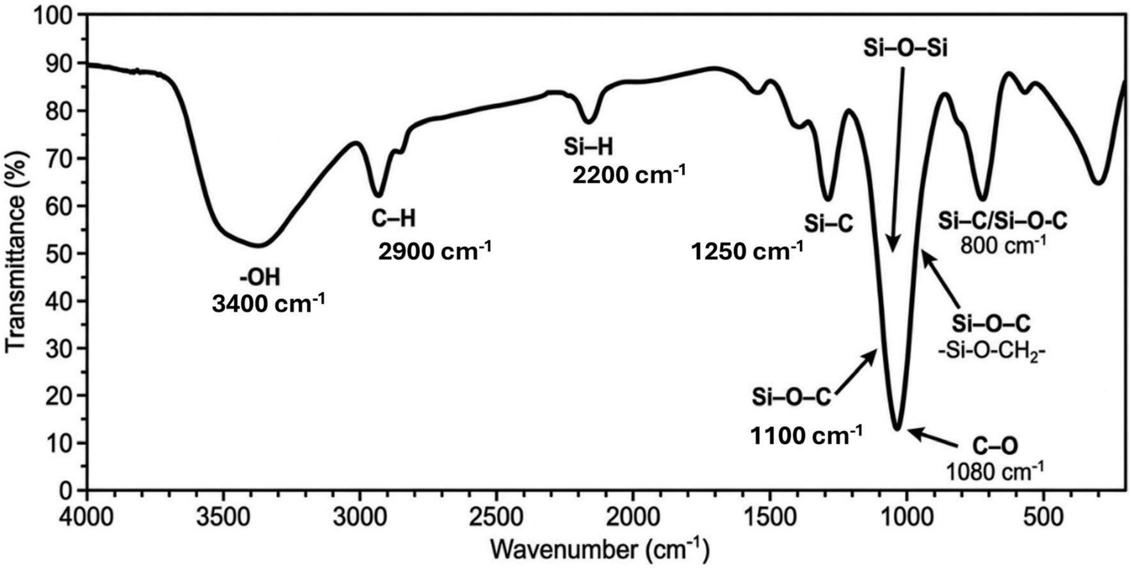


Fig. 3. Results of FTIR analysis.

4. Conclusions

In this study, we successfully developed an organosilane-based functional protective coating for wooden cultural artifacts and established a multidimensional sensing evaluation framework to monitor its efficacy. The research findings are summarized as follows.

1. Integration of Sensing Technologies: By employing optical colorimetric sensing, automated contact angle sensing, and FTIR chemical sensing, we provided a quantifiable method to perceive the surface and structural transformations of wood heritage materials. The results obtained by this approach demonstrated that sensing-based evaluation is essential for ensuring the long-term stability of cultural conservation treatments.
2. Preservation of Visual Integrity: Colorimetric sensing data confirmed that the developed MTMS-based coating maintains the original aesthetic value of characteristic Taiwan wood species. The total color difference (ΔE) for Taiwan red cypress and *Calocedrus* was merely 0.68 and 1.04, respectively, both of which are below the threshold of human visual perception.
3. Enhanced Hydrophobic Sensing Performance: The results of the hydrophobicity sensing analysis indicated that the developed material achieved a stable hydrophobic state, with

contact angles ranging from 90° to 120° across all tested wood species. This performance was significantly better than those of the Rainbow Paint brand and PEG-based control groups, the latter of which exhibited hydrophilic properties with sensed contact angles between 15° and 35°.

4. Verification of Consolidation Mechanism: The results of FTIR chemical sensing verified the formation of stable Si–O–C covalent bonds through the hydrolysis and condensation of MTMS with wood cellulose. This molecular integration, combined with excellent stain and acid resistance, confirms that our developed coating provides a durable protective network within the wood structure.

In conclusion, the organically modified silane material developed in this research aligns with biomimetic design concepts and offers a scientifically sound technique for wood artifact preservation. Future work will focus on the long-term sensing monitoring of these coatings under various accelerated aging conditions to establish standardized technical protocols for a wider range of cultural heritage assets, including ceramics and stone.

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