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RAPID COMMUNICATION

Simple separation of *Torreya nucifera* and *Chamaecyparis obtusa* wood using portable visible and near-infrared spectrophotometry: differences in light-conducting properties

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Introduction

The identification of wood species in artifacts of archeological/historical significance is important both for repairing and maintaining the artifacts and for understanding their historical and cultural backgrounds. For nearly 20 years, we have examined wood in artifacts by collecting minute, naturally detached fragments and observing them with light or scanning electron microscopy [1–3]. We found that the woods of *Torreya* sp. (Taxaceae) and *Chamaecyparis* sp. (Cupressaceae) were frequently used to construct Buddhist statues after the 8th century AD.

One problem with the above approach is that it is sometimes difficult to obtain samples with sufficient quality and quantity to make a definitive identification. For this reason, it is important to develop alternative methods for a non-invasive examination of artifacts. We have applied near infrared (NIR) spectroscopy to non-invasively identify wood species frequently used in wooden Buddhist statues. In doing so, we achieved a successful separation of *T. nucifera* and *C. obtusa* using multivariate analysis [4, 5]. However, it is considered that the separation of both species becomes difficult in the case of wooden Buddhist statues made more than several 100 years ago, because of the degradation of chemical compositions caused by exposure to circumferential condition for a long time. Then, other methods for separating both species without referring to the chemical compositions are desired.

In this study, we developed a simple method to separate *T. nucifera* and *C. obtusa* based on the difference in the light conductivities of their wood. We then evaluated the possibility of separating *T. nucifera* and *C. obtusa* using a portable photospectrometer.

Materials and methods

Sample preparation

Five wood specimens having radial and tangential faces with widths of more than 4 cm were selected from *Chamaecyparis obtusa* (TWTw 15, 75, 652, 9293, 21542) and *Torreya nucifera* (TWTw 852, 4332, 9272, 13662, 19683). The samples were collected from various sites in Japan and stored for 10–64 years in the wood library of the Forestry and Forest Products Research Institute (temperature 20–30 °C; humidity 50–80 %). Prior to the measurement, one set of radial and tangential surfaces was planed by a rotary planer to expose a fresh surface, and the other set of tangential and radial surfaces was left untouched (degraded). The prepared wood samples were kept in a room conditioned at a temperature of 20 (±2) °C and a humidity of 45 % (±5) for more than 3 weeks.

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Spectra acquisition

Five spectra were acquired from each wood sample surface (radial/tangential, sapwood/heartwood, fresh/degraded) in the visible and NIR (Vis–NIR) ranges. Because the original shapes of the wood samples were not uniform, the spectra could not be always obtained from a complete set of surfaces together in each sample. A portable photospectrometer (K-BA100R, Kubota Co., Osaka, Japan) was used to acquire Vis–NIR spectra in the range of 500–1000 nm at 2-nm intervals. Spectra were obtained in interactance mode, and the field of view of the detector was separated from the light source, forming a concentric ring around the detector. The diameters of the detector and the illuminator ring were 5 and 38 mm, respectively. The schematic diagram of the probe can be seen in Kobori et al. [6]. The integration time for each acquisition was 1200 ms. The light irradiated from the illuminator ring was conducted through wood sample by repeating transmission, reflection, absorption, and scattering within wood, and consequently a part of the light reached to the detector. The amount of photons acquired by the detector was converted to voltage for each wavelength. The accumulated voltage measured by the photospectrometer is regarded as the amount of light that reached to the detector, and therefore an indicator of the light conductivity of wood sample.

Measurement of wood density

Water immersion method was employed to measure wood density. A strip with thickness 1.5 cm was taken from a transverse surface of each sample using rotary saw. The weights of the strips at room temperature of 25 °C (W_a) and those of the strips in water (W_w) were measured. Water density at 25 °C was set to 0.997047 g/cm^3 [7], and the air dry density (D_a) was calculated from the following equation:

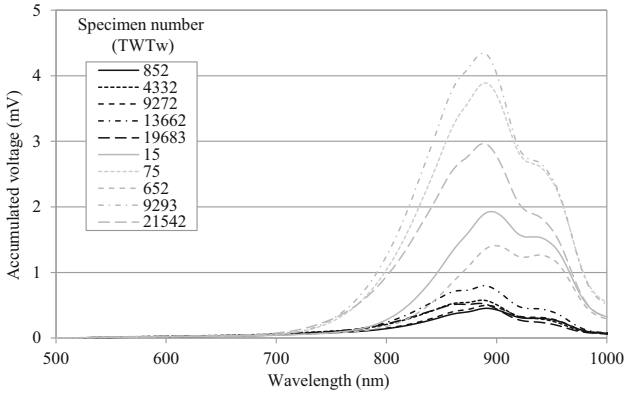

Fig. 1 Average of spectra for all specimens. *Black and gray lines* indicate *Torreya nucifera* and *Chamaecyparis obtusa*, respectively

$$D_a = 0.997047 W_a/(W_a - W_w).$$

Results and discussions

Figure 1 shows the average of the spectra for all specimens, and the spectra showed similar patterns for all specimens. Each spectrum increased from about 700 nm and reached maximum values in the range of 884–892 nm and of 886–900 nm for *T. nucifera* and *C. obtusa*, respectively. All specimens showed shoulder-shaped patterns around wavelengths of approximately 860 and 940 nm. As many absorption bands due to second or third overtones of OH and CH groups are contained in the wavelength region of 700–1000 nm [8], these absorbance may influence the spectral patterns. It should be noticed, however, that the spectral pattern of the accumulated voltage is quite different from absorbance or reflectance

Table 1 Averages of five spectra obtained from each surface

Fresh/Degraded		Fresh				Degraded				Wood density (g/cm^3)
Sap/Heart		Sapwood		Heartwood		Sapwood		Heartwood		
Face		Radial	Tangential	Radial	Tangential	Radial	Tangential	Radial	Tangential	
Torreya (TWTw No)	852	0.76		0.85		0.44		0.59	0.46	0.57
	4332	0.68		0.79	0.51	0.80		0.96		0.55
	9272	0.69		0.71	0.56	0.72	0.65	0.65	0.72	0.51
	13662			0.89	1.05	0.65		1.23		0.50
	19683	0.87		0.69	0.75	0.70	0.75	0.65	0.62	0.55
Chamaecyparis (TWTw No)	15	2.67		2.44	2.33	1.98		1.77	1.51	0.47
	75	2.57		5.45		4.28		5.24	2.88	0.53
	652	1.61		1.52	1.61	1.41	1.63	1.68	1.76	0.46
	9293	3.90		5.33	5.24	4.00		4.45	4.31	0.40
	21542			3.75	1.97			3.24	3.69	0.46

spectra, and thus band assignment cannot be performed with the measured spectra in Fig. 1.

The voltage values were extremely different between species, with the *C. obtusa* specimens always having higher voltage values than the *T. nucifera* specimens at wavelengths above 874 nm. The maximum values of all measured faces are shown in Table 1. These values varied from 0.44 to 1.23 for *T. nucifera* and from 1.41 to 5.45 for *C. obtusa*. As the differences were very significant among specimens, there does not seem to be trends in the differences between the fresh and degraded surfaces, between sapwood and heartwood, and between the radial and tangential faces.

In this study, the accumulated voltage values for *T. nucifera* and *C. obtusa* were completely different in the range of 874–1000 nm. This result shows that the light conductivity of *C. obtusa* was higher than those of *T. nucifera*, and that the portable Vis–NIR photospectrometer can be used to separate the woods of *Torreya* sp. and *Chamaecyparis* sp. without the need for complex spectral analysis. It is important to apply this newly developed method to historically important artifacts made after the 8th century AD. We previously identified historically valuable wooden artifacts made from either softwood or hardwood [9]. Now, the successful separation of *Torreya* sp. and *Chamaecyparis* sp. demonstrates the possibility of non-destructively identifying the woods of most of the Buddhist statues made in the above period.

It is also important to understand the mechanism underlying the difference in the light-transmitting properties from the far-red to the shorter NIR regions between the species. Differences in the light-transmitting properties have been reported in some wood species [10–13]. These differences were attributed to differences in wood density, anatomical structures, and so on. In this study, the difference in light conductive property between *T. nucifera* and *C. obtusa* does not seem to be caused by a difference in wood density (Table 1). To differentiate the effects of wood density on accumulated voltage from the effects of other species-dependent factors (e.g., anatomical structures), we performed an analysis of covariance (ANCOVA) with density as the covariate and species as the independent variable. The ANCOVA results revealed no significant effect of density ($P = 0.63$), while significant differences between species were observed ($P = 0.046$). This indicates that the light conductivity of wood was affected by species-dependent factors rather than by wood density. As differences in light conductance among wood tissues have also been reported in the branches of some wood species [10, 11], anatomical structures are considered to play an important role in light conductance. Anatomical structures are considered to be less severely affected by degradation with long time storage than chemical compositions [1–3]. For these reasons, the method that we have developed in this study may have a potential to confirm which species were used for Buddhist statues *T. nucifera* or *C. obtusa*, non-destructively. As *T. nucifera* wood poses helical thickenings on the inner surfaces of tracheid walls, they may influence light conductivity of the species.

However, there are not sufficient systematic studies that have investigated the behaviors of light in this wavelength range. To effectively utilize light in this range of wavelength to identify wood, it is necessary to systematically investigate the behavior of light in various wood species in the future.

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