Cipta *et al. Journal of Wood Science* (2022) 68:65
https://doi.org/10.1186/s10086-022-02072-z

Journal of Wood Science

ORIGINAL ARTICLE

Open Access

Identification of the wood species in the wooden sheath of Indonesian kris by synchrotron X-ray microtomography

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Abstract

A kris is a traditional dagger that originated in Indonesia. A kris is distinguished by its asymmetrical blade, which has layers of different metals bonded on its surface. Wood is the main material used to make the kris sheath. To preserve the knowledge about wood selection of the sheath, wood identification is a crucial first step. In the present study, we identified the wood species used to make the kris sheath. We performed synchrotron X-ray microtomography, which allows microscopic observation with minimum sample availability. Seven wooden kris sheaths were investigated. The results showed that synchrotron X-ray microtomography is suitable for observing the important microscopic anatomical features of the wood species in kris sheaths. We found that *Dysoxylum* spp., *Tamarindus indica*, and *Kleinhovia hospita* were used as sheath materials. We also visualized the spatial distribution of the prismatic crystals inside the *T. indica* and *K. hospita* xylem cells. Abundant crystals were present in *T. indica* arranged in longitudinal alignment inside the chambered axial parenchyma cells. The crystals were arranged in radial alignment inside the ray cells of *K. hospita*. The existence of abundant crystals in series may be important for the mechanical support of certain xylem cells.

Keywords: X-ray synchrotron microtomography, Indonesian dagger sheath, Wood identification, Traditional weapon, Non-destructive testing, Wood structure, Cultural heritage, Mineral inclusion

Introduction

Kris is the name of a traditional double-edged dagger from Indonesia. Some kris have straight blades, while others have curved blades. The kris blade has a distinctive pattern of welded layered metals on the surface [1]. This dagger was initially used as a weapon, but it has evolved into a cultural object with distinctive historical and artistic worth. The modern form of the kris may have existed before the fourteenth century on the island of Java, Indonesia [2]. In later centuries, the kris culture assimilated with the cultures of other nations in Southeast Asia.

Humans have used wood for thousands of years, including as weapons [3]. Wood is also used to manufacture parts of the kris. Although the blade of the kris is the most important component and several studies have been performed to investigate the blade [1, 4], the wooden hilt and sheath are also integral parts (Fig. 1a). When choosing the material for making a kris sheath to protect the kris blade, there are a few things to consider. There is a tendency that the type of wood used to make the kris sheath indicates the social status and has a philosophy. However, wood selection for the kris sheath has changed because of the scarcity of wood materials and other factors. The valuable knowledge about the wood preference may disappear owing to this shift. Therefore, wood identification is crucial for preserving knowledge about the kris sheath. Nevertheless, identifying wood species of the kris sheath by scientific methods has not been widely performed.

Usually, wood identification is performed by observing anatomical characteristics of the wood. Therefore,

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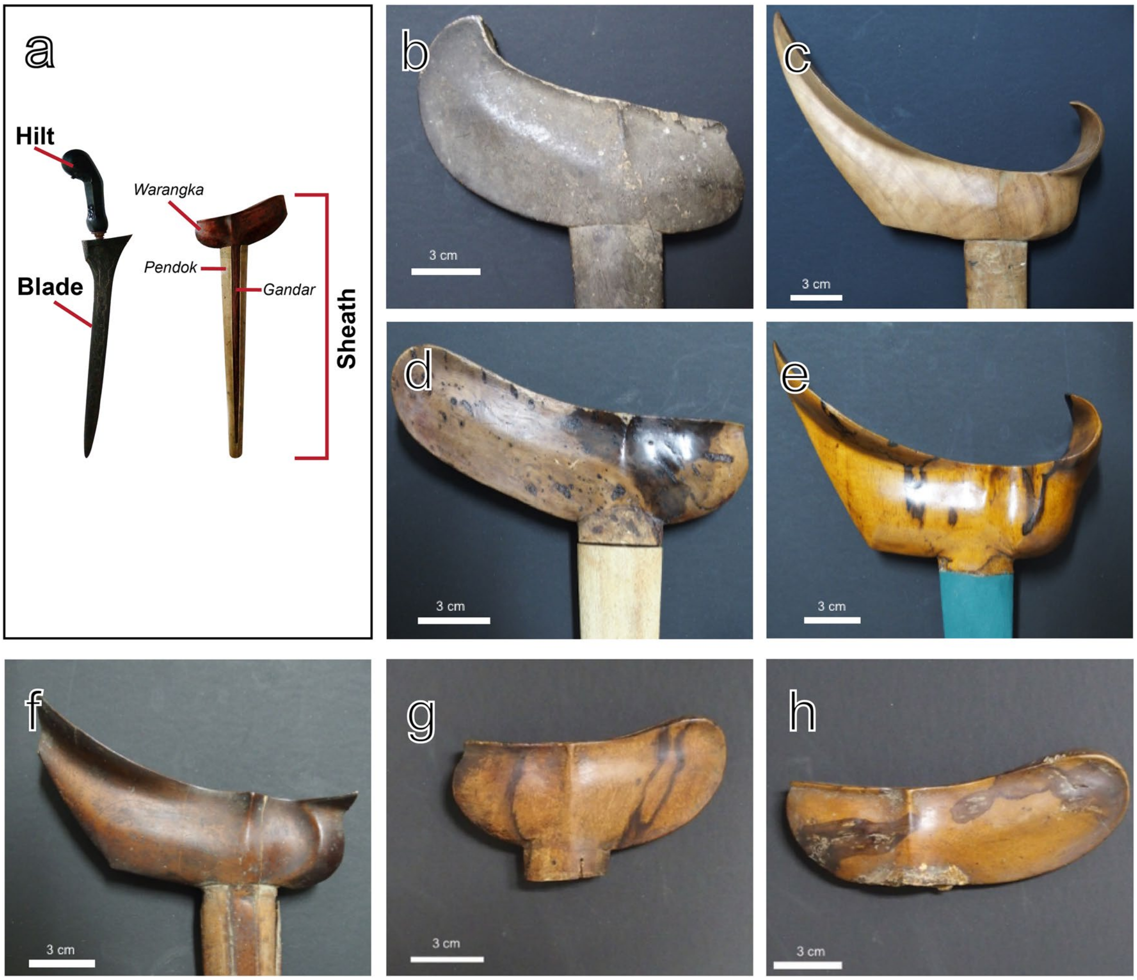

Fig. 1 **a** Definition of the kris main parts. Photographs of the kris sheaths: **b** 1, **c** 2, **d** 3, **e** 4, **f** 5, **g** 6, and **h** 7

a certain amount of sample needs to be removed from the object for observation. However, for cultural objects, sampling from the object must be carefully managed. Therefore, the minimum amount of the object needs to be removed, but the amount should be sufficient to understand the wood anatomical characteristics. For a relatively small sample, it is difficult to obtain an appropriate wood section. Scanning electron microscopy (SEM) is one option to observe a small sample [5]. However, this procedure requires significant preparation that can damage the sample. In addition, three orthogonal planes—the transverse, radial, and tangential planes—are typically used to observe the anatomical properties of wood. The SEM technique is not sufficiently adaptable to visualize the surfaces of these planes.

Combined low-resolution neutron and conventional X-ray computed tomography (CT) has been used to investigate kris sheath materials [6]. The advantages of this technique are the minimal effort for sample preparation and the possibility of reconstructing images in a volumetric way. In addition, sectioning in any direction is possible, which allows the important transverse, radial, and tangential planes of wood to be revealed. However, the resolution of this method is not sufficiently high to obtain the important microscopic features for wood identification. Synchrotron X-ray microtomography (SRX-ray μCT) is an alternative method to obtain detailed microscopic features [7, 8]. Therefore, in this study, we used SRX-ray μCT to identify the wood species in the kris sheath. This technique is suitable for revealing the microscopic features of wood with minimum sample availability and without significant damage to the sample. Therefore, the sample can be used for other analyses. In addition, segmentation based on the densities of the materials [9] can be performed to reveal the spatial distribution of the mineral inclusions in the xylem cells.

Materials and methods

Wood samples and image acquisition

We investigated seven Javanese kris sheaths, as shown in Fig. 1b–h. The shapes of the sheaths are typical of the Javanese sheaths produced in the region near the Province of Central Java and Special Province of Yogyakarta in Indonesia. The first type is *gayaman*, which was carved, such as gayam fruit (*Inocarpus fagifer*) (Fig. 1b, d, g, and h). The second type is *ladrang* or *branggah*, which was carved like the shape of a ship (Fig. 1c, e, and f). Small wood fragments with a maximum diameter of 0.7 mm and 5 mm in length were extracted from the *warangka* part of each sample.

To obtain the CT data, we performed SRX-ray μCT experiments at beamline 20XU of the SPring-8 facility in Harima, Hyogo Prefecture. Using a high-resolution camera, 1800 transmission images were recorded (2048 × 2048 pixels). We scanned with resolution of 0.472 μm/pixel for sheaths 1–5 and resolution of 0.508 μm/pixel for sheaths 6 and 7. We reconstructed the image data to convert the transmission images into cross-section image slices (2048 in total).

We used the volume graphic software VGStudio MAX 2.2 (Volume Graphic GmbH, Heidelberg, Germany) to process the images from the cross section into three-dimensional (3D) images and obtain a virtual section from different planes by virtually cutting the set of images. Most of the images were cut based on the three orthogonal planes of wood: the transverse, radial, and tangential planes. A single image slice (one pixel in thickness) only represents limited thickness of the real object. To optimize visualization of the CT images, pseudo-micrographs were prepared using the same software to obtain information from a thicker part by combining multiple slices in one image. Therefore, we could mimic image visualization with similar depth information to that of an optical micrograph.

Wood species identification

Wood species identification was started by examining the observable anatomical characteristics of the different planes by following the description of the International Association of Wood Anatomists (IAWA) [10]. We used the online anatomical characteristic database provided by the online wood database InsideWood [11] to filter a number of species candidates. The wood identification key reference of Southeast Asia and the Western Pacific was also used [12]. We also referred to some publications to obtain additional information regarding wood selection to make the kris sheath [13–16].

Results

Some important anatomical features were extracted and visualized by the SRX-ray μCT technique combined with volume graphic software. The results are given in Table 1. Reconstructed images of the virtual sections in two dimensions of the samples obtained by processing the images from various planes using volume graphic software are shown in Figs. 2 and 3. Finally, prediction of the wood species was performed based on the key characteristics of the anatomical features. Several microscopic anatomical features can be revealed using this technique, including the vessel characteristics (vessel grouping, perforation plate, and pit type), ray parenchyma characteristics (ray width, rays per millimeter, ray cellular composition, and ray cellular composition), axial parenchyma type, fiber type, and prismatic crystal location.

Sheaths 1, 2, and 5

The anatomical characteristics of kris sheaths 1, 2, and 5 were identified to be *Dysoxylum* spp. The vessels were solitary and in radial multiples of 2 (Figs. 2a1, b1, and 3b1). The perforation plate was simple. The intervessel pits were alternate. The vessel-ray pits were similar to the intervessel pits, and the rays were 1–2 cells in width (Fig. 2a2 and b2). The number of rays per millimeter was

Table 1 Identification results of likely species of wood used in the kris sheaths

Sheath No.	Number in Fig. 1	IAWA code	Species prediction	Family
1	b	13, 22, 30, 47, 65, 80, 82, 85, 86, 97, 106, 115, 136, 142	*Dysoxylum* sp.	Meliaceae
2	c	13, 22, 30, 47, 65, 80, 82, 85, 86, 97, 106, 115,	*Dysoxylum* sp.	Meliaceae
3	d	13, 22, 30, 47, 58, 80, 81, 83, 97, 104, 115, 136, 142	*Tamarindus indica*	Fabaceae
4	e	13, 22, 30, 77, 97, 107, 111, 115, 136, 137, 138, 141	*Kleinhovia hospita*	Malvaceae
5	f	13, 30, 46, 65, 80, 86, 97, 115	*Dysoxylum* sp.	Meliaceae
6	g	13, 30, 47, 58, 80, 81, 89, 97, 104, 115, 136, 142	*Tamarindus indica*	Fabaceae
7	h	13, 22, 30, 48, 77, 97, 107, 111, 115, 136, 137, 138, 140, 141	*Kleinhovia hospita*	Malvaceae

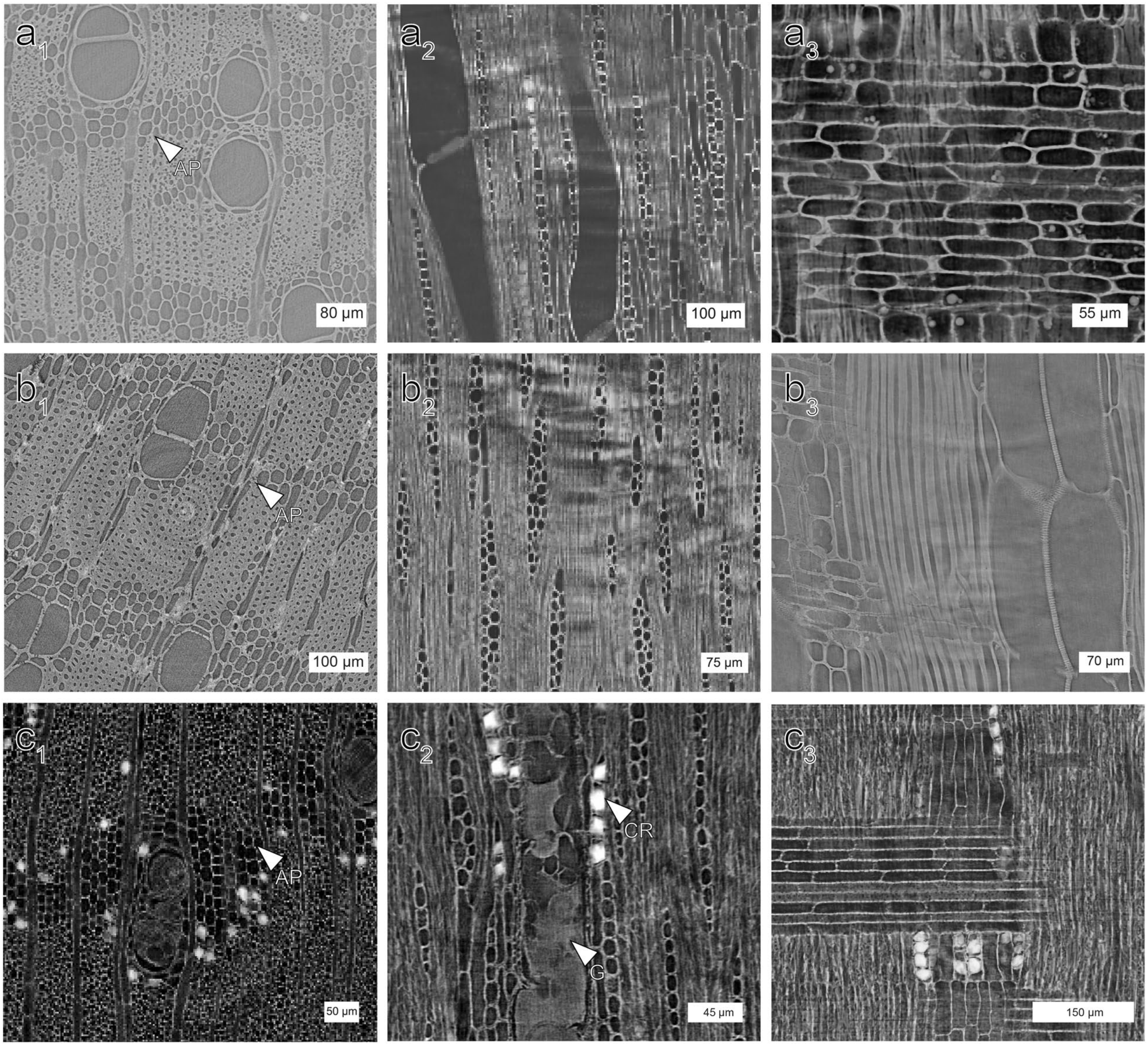

Fig. 2 Virtual sections and 3D reconstruction of sheath (**a_1**–**a_3**) 1, (**b_1**–**b_3**) 2, and (**c_1**–**c_3**) 3. Transverse sections (**a_1**, **b_1**, **c_1**), tangential sections (**a_2**, **b_2**, **c_2**), and radial section (**a_3**, **b_3**, **c_3**). *AP* axial parenchyma, *CR* prismatic crystal, *G* gum

7–9, and the cellular composition of the rays was body ray cell procumbent with one row of upright and/or square marginal cells. The axial parenchyma types were winged-aliform narrow bands, and the bands were more than three cells wide (Figs. 2a1, b1, and 3b1). Septate fibers were observed in all of the samples, but they were more dominant in sheath 5 (Fig. 3b2). Prismatic crystals were absent for sheaths 2 and 5, but a few prismatic crystals were observed in sheath 1. The crystals were located in chambered axial parenchyma cells (Fig. 2a2).

Sheaths 3 and 6

The anatomical characteristics of sheaths 3 and 6 belonged to *Tamarindus indica*. The pseudosections of the samples are shown in Figs. 2c1–3 and 3c1–3. The vessels were solitary with radial multiples of 2–3 (Figs. 2c1 and 3c1). The perforation plate was simple. The intervessel pits were alternate. The vessel-ray pits had distinct borders (Fig. 3c3). Gum or other deposits were present in the vessels (Figs. 2c2 and 3c1). The rays were 1–2 cells in width, and the type of ray cells was procumbent (Fig. 2c3). The

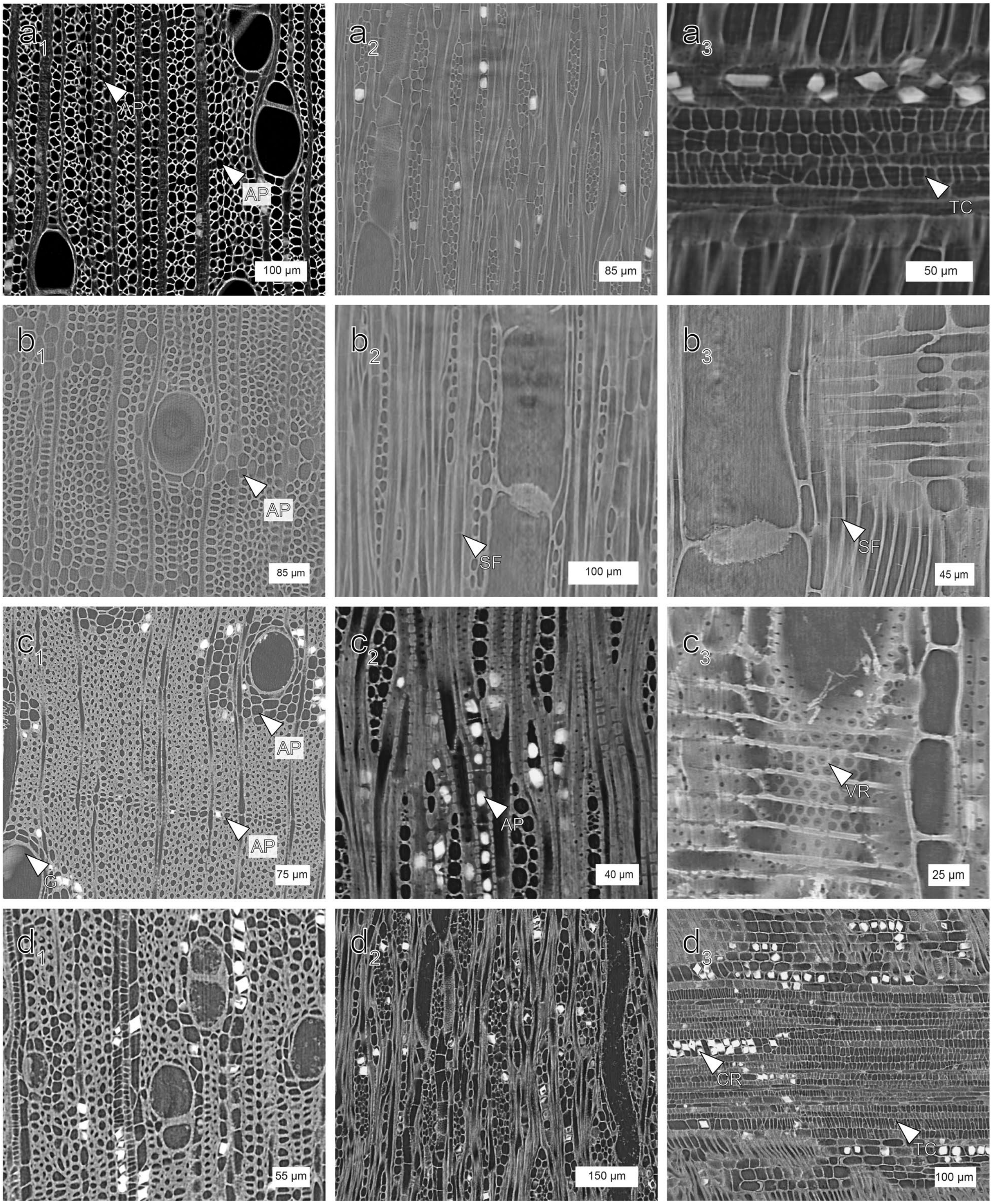

Fig. 3 Virtual sections and 3D reconstruction of sheaths (**a₁**–**a₃**) 4, (**b₁**–**b₃**) 5, (**c₁**–**c₃**) 6, and (**d₁**–**d₃**) 7. Transverse sections (**a₁**, **b₁**, **c₁**, **d₁**), tangential sections (**a₂**, **b₂**, **c₂**, **d₂**), and radial sections (**a₃**, **b₃**, **c₃**, **d₃**). *AP* axial parenchyma, *SF* septate fiber, *VR* vessel-ray pits, *CR* prismatic crystal, *G* gum, *TC* tile cell

number of rays per millimeter was 11–12. The axial parenchyma types were lozenge-aliform and confluent (Figs. 2c1 and 3c1). In addition, axial parenchyma in marginal bands was present in sheath 6 (Fig. 3c1). The fiber was non-septate. There were abundant prismatic crystals (Figs. 2c1 and 3c1), and the prismatic crystals were distributed in the chambered axial parenchyma cells (Figs. 2c2 and 3c2).

Sheaths 4 and 7

We predicted that the wood species used to make sheaths 4 and 7 was *Kleinhovia hospita*. The vessels were solitary and in radial multiples of 2–3 (Fig. 3a1 and d1). The perforation plate was simple. The intervessel pits were alternate. The vessel-ray pits had distinct borders. The rays were 1–4 cells in width (Fig. 3a1 and d1), and they were composed of body ray cell procumbent with 2–4 rows of upright and/or square marginal cells. The number of rays per millimeter was 8–9. Tile cells were found among other types of ray cells (Fig. 3a3 and d3). The axial parenchyma type was diffuse-in-aggregate (Fig. 3a1). Prismatic crystals were distributed in chambered (Fig. 3d3) and non-chambered (Fig. 3a3) upright and square ray cells (Fig. 3a3), as well as in non-chambered axial parenchyma.

Spatial distribution of the prismatic crystals

Abundant prismatic crystals were observed in the samples of sheaths 3, 4, 6, and 7. The samples belonged to two species: *T. indica* (sheaths 3 and 6) and *K. hospita* (sheaths 4 and 7). The patterns of the crystals for these two species were different. In general, two types of distributions were observed: longitudinal alignment of the crystals inside the axial parenchyma cells for *T. indica* (Fig. 4) and radial alignment of the crystals inside the ray cells for *K. hospita* (Fig. 5). The distribution of crystals inside the axial parenchyma cells with aliform type is shown in Fig. 4. In the aliform type, the axial parenchyma cells were distributed around the vessels. Many crystals were longitudinally aligned inside the axial parenchyma cells around the vessels (Fig. 4). Meanwhile, the prismatic crystals were extensively distributed in the ray cells of *K. hospita*, as shown in Fig. 5. The crystals were grouped in radial alignment with short or long series. The crystal groups did not occupy entire ray cells, but they were scattered among non-crystal ray cells.

Discussion

We have identified the wood species used for the wooden kris sheaths based on the anatomical characteristics of samples of the sheaths by SRX-ray μCT. All of the

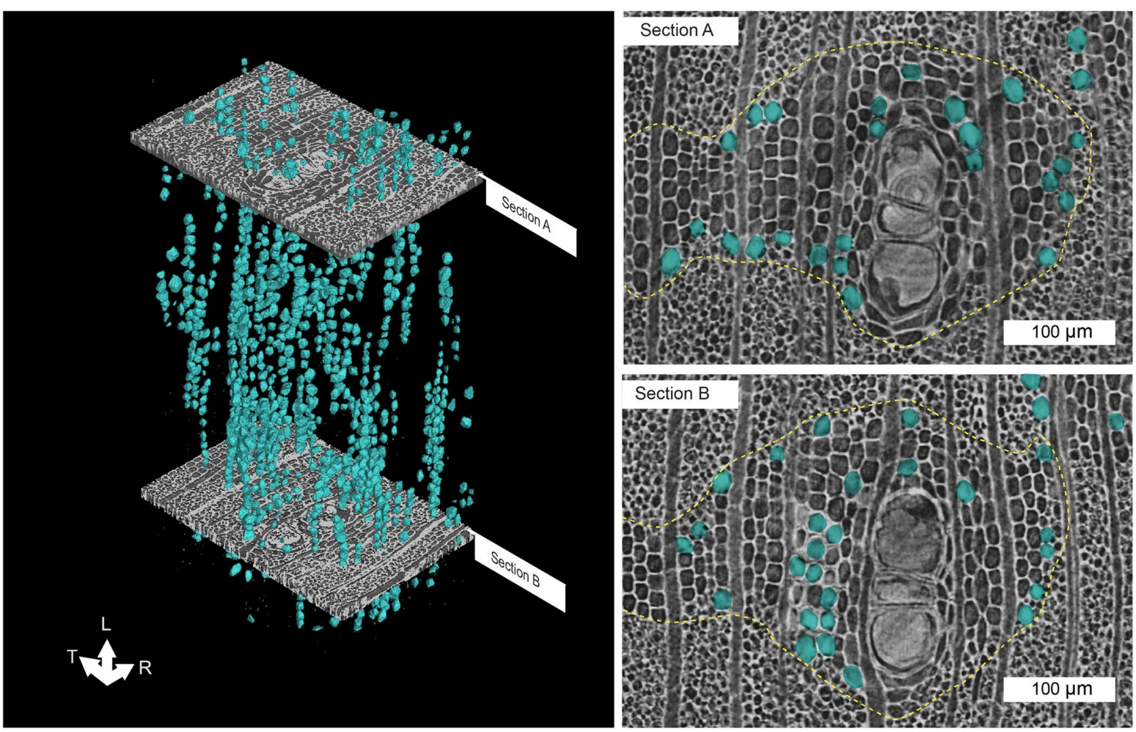

Fig. 4 Spatial arrangement of the prismatic crystals surrounding the vessels in sheath 3. Left: 3D visualization of the wood by isolating the prismatic crystals (blue) and two consecutive transverse sections (sections A and B). Right: 2D views of sections A and B. The yellow dashed line is the boundary between the axial parenchyma and fiber cells. *L* longitudinal direction, *R* radial direction, *T* tangential direction

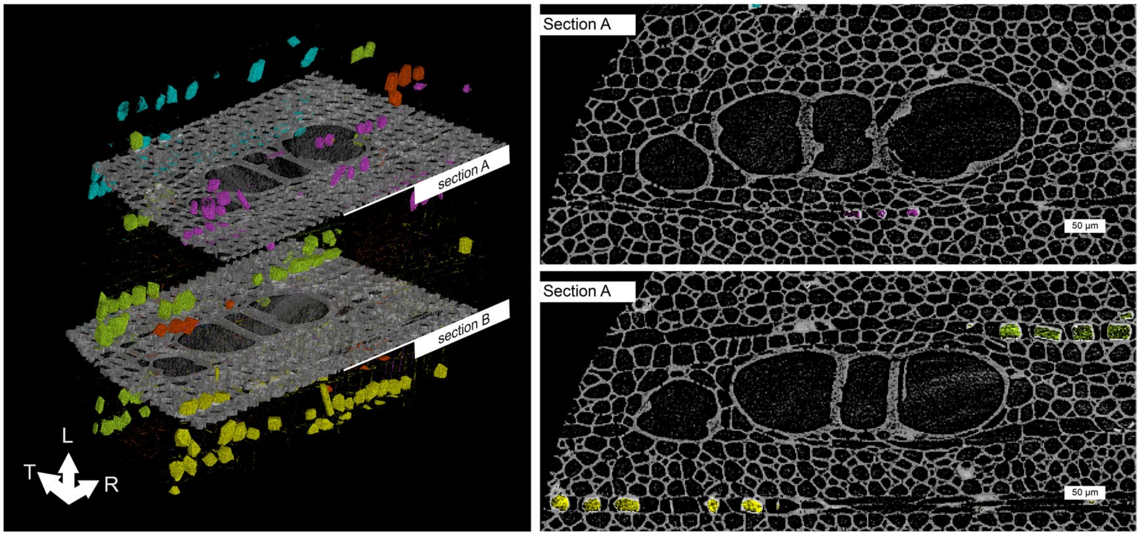

Fig. 5 Spatial arrangement of the prismatic crystals surrounding the vessels in sheath 4. Left: 3D visualization of the wood by isolating the prismatic crystals (blue, green, red, purple, and yellow particles) and two consecutive transverse sections (sections A and B). The different colors of the particles show different tangential positions of the crystals. Right: 2D views of sections A and B. *L* longitudinal direction, *R* radial direction, *T* tangential direction

samples were identified to be hardwood species (e.g., *Dysoxylum* spp., *T. indica*, and *K. hospita*) (Table 1). This is not surprising, because only a few species of softwood belong to the families Araucariaceae, Pinaceae, and Podocarpaceae grown in Southeast Asia and the Pacific [12]. The wood species used for making sheaths 1, 2, and 5 contained septate fiber, which is commonly observed in the genus *Dysoxylum*, family Meliaceae. Several species in the Meliaceae family, including some in the genera *Entandrophragma* and *Guarea*, have nearly identical anatomical features as *Dysoxylum*. However, based on their geographical origin, the samples are most likely from the genus *Dysoxylum*. Furthermore, *Dysoxylum acutangulum* has traditionally been utilized as kris sheath material [17]. Septate fiber is a type of fiber containing thin transverse primary vessels with a thin transverse primary vessel wall [10, 18]. Another characteristic of this genus is the appearance of banded axial parenchyma [12]. In sheaths 3 and 6, one of prominent characteristics of *T. indica* was the appearance of gum or other deposits in the vessels. In addition, crystals were present in the chambered axial parenchyma. The existence of tile cells for sheaths 4 and 7 is one of the key characteristics of *K. hospita*. Tile cells occur in only 1% of hardwoods [19], and they are an important characteristic in distinguishing the Malvales members. The type of tile cells of this species is *Durio* type. The tile cells in sheaths 4 and 7 had the same height as the procumbent cells [10].

In this study, part of the sample observed was approximately 1 mm in both diameter and length. With a small amount of sample, information about the wood porosity and growth-ring morphology that is important for wood identification may not be obtained [5]. However, by utilizing SRX-ray µCT, we could obtain features such as perforation plate, morphology of pits, septate fibers, tile cells etc. that can take time and effort to obtain using conventional sectioning method. When using the sectioning method, some iterations are required to get appropriate sections to observe such features. However, these iterations will be difficult to apply due to limited sample availability. For SRX-ray µCT, infinite repeated sectioning is possible. Therefore, compared to traditional sectioning, SRX-ray µCT is better to have more successful wood identification with minimum sample size, while keeping the sample is still intact.

A kris sheath is typically made of selected materials. A high-quality kris sheath is usually made of fine, esthetic, rare, and expensive wood [13, 15, 17, 20]. Several wood species are often used for kris sheaths, such as *Santalum album*, *K. hospita*, *Dysoxylum acutangulum*, *Wrightia javanica*, *Melia azedarach*, *Murraya paniculata*, *Ficus septica*, *Dalbergia latifolia*, *Mesua ferrea*, *Tectona grandis*, *Cassia siamea*, *Pterocarpus indicus*, *T. indica*, and *Cassia laevigata* [13–17]. Sheaths 4 and 7 were *K. hospita* with dark-brown stains on their surfaces (Fig. 1e and h). The appearance of a dark-brown stain was one of the considerations for selecting *K. hospita* [17]. Sheaths 3 and 6, which were made of *T. indica*, also had dark-brown stains on their surfaces. Although *K. hospita* species can be identified through the appearance of a dark-brown stain, to avoid misidentification, observation of the wood anatomy is more accurate to distinguish the wood species. Meanwhile, *Dysoxylum acutangulum,* also known as *trembalo* (local name in Indonesia), is preferable, because this species has a beautiful grain.

In general, xylem tissue and the surrounding air provide sufficiently fine contrast when observed by SRX-ray μCT. Because mineral inclusions have higher density than xylem tissue, they can be identified in xylem cells [21]. By performing simple segmentation, we reconstructed the mineral inclusions with the prismatic crystal shape in volumetric space. The crystal may have some functions, such as protection against insects, detoxification of toxic substances, tissue mechanical support, as well as light gathering and reflectance [21–26]. As previously mentioned, we observed two different patterns of the crystal distribution. First, on *T. indica*, the crystals in longitudinal alignment in the axial parenchyma cells around the vessels as if they were pile foundation on a building structure. Second, radial short and long series of crystals were observed on *K. hospita* as if they were beams of load bearing wall on a building structure. Similar observation was conducted on bark structure and suggested that the presence of abundant prismatic crystals contributed as mechanical reinforcement to prevent compression fracture [27]. The spatial distribution of the crystals may influence the mechanical function to strengthen the structure of the vessel for water conduction in many species with axial parenchyma arrangements that encircle the vessel entirely (vasicentric, aliform, and others), mainly belonging to the family Fabaceae, including *T. indica.* The radial alignment of the crystals in *K. hospita* may be useful in strengthening the structure of the ray cells.

Conclusions

We have identified the wood species in the sheaths of Indonesian kris. This study was the first attempt to identify the wood species in wooden kris sheaths based on microscopic observation of the anatomical features of the wood species. We performed SRX-ray μCT of small samples of seven kris sheaths. Therefore, we avoided excessive wood sampling of the objects. Another advantage of this method is that the samples can be used for further analyses. This technique allowed us to visualize the wood microstructure in the conventional orthogonal planes (transverse, radial, and tangential planes) in two dimensions, as well as to reconstruct the microstructure in three dimensions. For the seven wooden sheath samples investigated in the present study, sheaths 1, 2, and 5 were *Dysoxylum* sp., sheaths 3 and 6 were *T. indica*, and sheaths 4 and 7 were *K. hospita.* The SRX-ray μCT technique allowed us to reveal the spatial distributions of the prismatic crystals in *T. indica* and *K. hospita.* The distributions of the crystals were not random. The spatial arrangement of the crystals might have a mechanical function in certain cells.

Abbreviations

SRX-ray μCT: Synchrotron X-ray microtomography; CT: Computed tomography.

Acknowledgements

HC thanks the Indonesian Endowment Fund for Education (LPDP) for supporting and funding his Master's degree program at Kyoto University (Japan) in 2016–2018. HC and WDN thank Dr. Fajar Waskito and Mr. Taufiq Hermawan for providing the kris sheath samples. The SRX-ray μCT experiments were performed at SPring-8 (Japan) with the approval of the Japan Synchrotron Radiation Research Institute (Proposal Nos. 2016B1743 and 2017B1761). This research was partly presented at the 67th Annual Meeting of the Japan Wood Research Society in Fukuoka, Japan, 2017 and PRWAC 2017 (The 9th Pacific Regional Wood Anatomy Conference) in Bali, Indonesia, 2017. We thank Edanz (https://jp.edanz.com/ac) for editing a draft of this manuscript.

Author contributions

HC was a major contributor to writing the manuscript. HC, WDN, and JS conceived and designed the study. HC and ST performed the experiments and analyzed the data. HC and JS performed wood identification. JS edited the manuscript and supervised the work. All authors read and approved the final manuscript.

Funding

This study was supported by a Grant-in-Aid for Scientific Research on Innovative Areas (Grant Number 18H05485) from the Japan Society for the Promotion of Science.

Availability of data and materials

The data sets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare they have no competing interests.

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Received: 27 October 2022 Accepted: 8 December 2022
Published online: 15 December 2022

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