Journal of Cultural Heritage 73 (2025) 110–121

Contents lists available at ScienceDirect

Journal of Cultural Heritage

journal homepage: www.elsevier.com/locate/culher

Original article

Bridging technology and culture: X-ray µCT-based wood identification of Sub-Saharan African heritage

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ARTICLE INFO

Article history:
Received 16 January 2025
Accepted 3 March 2025

Keywords:
Cultural heritage
Sub-saharan african heritage
Tropical wood species
X-ray µct
wood identification
wood selection

ABSTRACT

Wood identification of cultural heritage objects is vital for facilitating their international travel, providing invaluable information for conservation strategies and improving our understanding of the objects' historical and cultural context. To date, wood identification is most commonly performed using techniques that rely on sampling, which is especially undesirable for valuable cultural objects. X-ray micro-tomography (µCT) offers a non-destructive alternative for gaining insight into the material composition of objects. It is a tool for identifying the wood species by visualizing the internal wood structure without changing the object. However, obtaining sufficiently high-resolution anatomical images that can be used for identification remains a challenge, particularly when examining diverse heritage objects.

This study applies µCT for the wood identification of 20 heritage objects from the Royal Museum for Central Africa (RMCA, Belgium), showcasing the efficacy of this non-invasive technique. Despite variations in the size, shape, and material composition of the objects, successful wood identification was achieved for all objects. Since two objects contained more than one wood species, the total number of identifications was 22, of which 18 were to the species level. For the four remaining samples, wood identification was achieved at the genus level (3 samples) or identified as a liana (1 sample).

Additionally, by obtaining a wood identification through X-ray µCT images, the physical and mechanical properties of the wood species were discussed in relation to the objects' original context and function. Specifically, lightweight wood species were found in objects with a portable function such as masks and a toy, while low-durability wood used in a funerary object could be linked to its symbolic role. Two musical instruments were identified as being made from wood species known for their acoustic qualities. These findings highlight the significant potential of advanced non-destructive imaging using µCT for wood identification, providing much-needed material and contextual insights into previously understudied museum collections.

1. Introduction

Wood represents one of the primary materials in many heritage collections. As a commodity that was both readily available throughout time and across continents, it has offered artisans a versatile medium for creative expression in a wide range of applications [1–3]. Identifying the wood species present in heritage objects is a recurring demand, both in private and museum collections. Possibly the most pressing incentive for this material analysis is that knowledge of the wood species is required for international travel. Whether for travelling exhibitions, loans or art trade, legal frameworks such as the Convention on the International Trade in Endangered Species (CITES) or the US Lacey Act require a wood identification when an object crosses the border

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https://doi.org/10.1016/j.culher.2025.03.001
1296-2074/

[4,5]. Wood species identification also allows collection managers and conservators to optimize the objects' preservation, as well as the best restoration treatments [2,6]. Lastly, determining which tree species an object is made of can significantly improve the cultural and historical understanding of the object. The species selection for each object attests to the ecological provenance of the object, the craftsmanship and dedication of the maker, and their knowledge of the material [7–9].

Despite the many advantages to the material understanding of a cultural heritage collection, systematic wood identification is rare in museum collections. This is partly due to the disadvantages of classic analysis methods, as wood identification is most commonly established through microscopical study of anatomical features, requiring a sample to be taken of the object. This destructive analysis, relying on a sample of at least 1 mm^3, permanently alters the object's appearance and cannot be performed on fragile or small objects without damaging their stability [10,11]. Although new and promising methods are being developed for fast and accurate wood identification, most still rely on a (minimal) sampling and/or on still-growing reference databases [12]. This is true for genetic profiling through DNA analysis [13,14], and chemical fingerprinting [15,16]. Moreover, although both techniques require a sample no larger than a splinter, they cannot be applied easily to heritage objects containing 'contaminating' materials. Finishing layers such as pigments or patinas on the surface of the object, as well as consolidation treatments where resins penetrated the wood structure, might disrupt the profiling of the sample.

Approaches that do not require invasive sampling, such as lab- or synchrotron-based X-ray micro-computed tomography (µCT) [17–22], X-ray fluorescence spectroscopy [4,23] and NIR imaging [24–26] have been rapidly developing over the past 20 years. By far the most proven, accessible, and used technique among these is X-ray µCT. Visualizing the internal wood structure, this technique relies on the same anatomical analysis as traditional microscopic studies. Case studies over the past ten years have proven the validity of the technique, highlighting the importance of a high resolution and the challenges of achieving the necessary image quality to visualize the diagnostic features. Nevertheless, most successful case studies utilizing this technique for wood identification are limited to one or two artefacts, with small enough dimensions to achieve the desired resolution [27–30]. Thereby, the full potential of X-ray µCT for a systematic wood identification of heritage collections, especially for those objects that vary in size, shape and materials, has not been explored before.

This paper presents a selection of 20 cultural objects that were scanned using X-ray µCT for wood identification. The objects are all part of the cultural collection of the Royal Museum for Central Africa, Belgium. Given that most of these objects were collected in bulk during the Belgian colonial period, much of the context surrounding the extensive collection, originating mainly from the Democratic Republic of the Congo (DRC), has been lost and remains under-documented [31]. A material study can add some much-needed knowledge about the collection. The selected 20 objects cover a wide range of sizes and shapes, as the dimensions and positioning of the objects in the scanner are one of the determining factors of the achieved resolution. In addition, objects with metals, glass and pigments were included in the study, as these highly attenuating materials have a potentially negative effect on the resulting X-ray µCT scans, causing image artefacts and loss of information. Objects showing past insect activity were included too, as the damage these wood borers caused could potentially limit the amount of 'intact' wood anatomy to be observed. One consolidated object, treated with an impregnated resin to strengthen structurally damaged wood, was included to investigate the impact of the resin on the visibility of the wood anatomy in the scans.

2. Research aim

The selection of 20 Sub-Saharan African heritage objects, differing in size, material composition and shape, serve to illustrate both the possibilities and limits of the technique for botanically identifying wood species. Following research questions are at hand: 1) which resolution can we achieve with a wide range of unique objects; 2) is it possible to identify the wood species based on the µCT scans given this variation?; 3) If wood identification is successful, can we link the wood properties to the object's original context, the function of the object, the selection of the tree from which the object was carved and the craftmanship and knowledge necessary to consider the specific density, durability, acoustic and aesthetic qualities of the wood incorporated in each object?

3. Materials and methods

3.1. Object selection

Table 1 lists the 20 objects selected to represent the wide variety in the RMCA collection. We followed the museum's database tool for the description of the objects. Five broad categories were used (based on typology and/or function), with four objects per category: sculptures, masks, objects of use, musical instruments and power objects. This last category refers to objects that are ascribed a power by their source community. The table includes the museum registration for each object – EO numbers refer to the 'ethnographic' collection; MO numbers to 'musicology' and SJ numbers to the collection in the museum held on behalf of the Jesuit order. The culture of origin is given, as well as the objects' dimensions. The last column describes any factors that can determine how closely the object could be positioned to the X-ray source in the scanner (which impacts the resulting resolution) or influences the legibility of the scanned wood anatomical information.

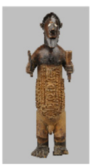
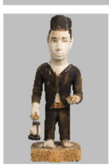
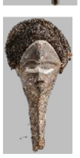
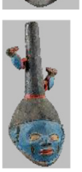
3.2. Scanners

We used two state-of-the-art scanners at the UGent Centre for X-ray Tomography [32]: HECTOR and TESCAN CoreTOM. HECTOR (High Energy CT scanner Optimised for Research) allows objects of up to one meter high and 100 kg in weight to be mounted on the rotation stage inside the scanner room. The high energy X-ray tube (up to 240 kV) and a 2880×2880 pixel flat-panel detector allow to acquire high-quality µCT scans at up to 3 µm voxel size of objects containing even high-attenuating materials [33]. The TESCAN CoreTOM scanner is a commercial system from the former UGCT spin-off company XRE (now part of the TESCAN Group a.s.). This scanner is equipped with an X-ray tube with maximum 180 kV and a 2856×2856 pixel flat panel detector. Objects of maximum 1 meter in height and 45 kg in weight can be mounted on the rotation stage.

3.3. Region of interest scans (ROI)

For the purpose of wood identification, we made Region of Interest (ROI) scans, which allowed us to aim for the highest possible resolution for each object. As the resolution (defined in this paper as reconstructed voxel size) depends on the source-to-object and object-to-detector distance, the dimensions and shape of the 20 objects were a determining factor in the achieved resolutions: positioning the object as close as possible to the X-ray source without colliding with the scanner during its full turn on the rotation stage, maximizes the magnification of the internal wood structure. Customized set-ups, including tailor-made supports were needed to facilitate positioning to optimize the resolution of the ROI scans.

Table 1
List of 20 African heritage objects according to their (broad) typology. A short description is given alongside a photo of the object, as well as their museum registration number, culture of origin (if known), dimensions and any factors that might have an impact on the µCT scan.

Object photo	Object description	Registration number	Culture	Dimensions (cm)	Impacting factor for ROI scan (shape, materials, condition)
Sculptures					
	Kneeling figure	EO.1949.6.1	Unknown	9.5 × 2.1 × 2.1	Homogenous shape
	Statue	EO.1951.75.1	Beembe	34.5 × 12×9.5	Homogenous shape
	Elephant sculpture	EO.1948.20.200	Chokwe	9.7 × 7.1 × 23.6	>1 wood species present in object
	Funerary statue	EO.0.0.1040–4	Yombe	48×17.5 × 16.5	Insect damage – highly attenuating materials (metal nails in arm, pigment layer)
Masks					
	Mask	EO.0.0.15404	Luluwa	58×29.7 × 18.5	Highly attenuating materials (pigment)
	Mask	SJ.1975	Pende	52×26×16	Insect damage – highly attenuating materials (pigment)
	Mask	EO.1951.35.5	Lega	22.4 × 14.1 × 3.3	Insect damage – old consolidation treatment – homogenous diameter
	Mask	EO.1998.24.1	Yoruba	47×18×36	Highly attenuating materials (pigment and metal nails)
Objects of use					
	Crocodile toy	EO.1979.1.887	Unknown	8.5 × 104×7.3	Large object
	Knife	EO.0.0.39806	Zande	33×5 × 5.8	Highly attenuating materials (metal blade, glass beads)
	Pipe	EO.1957.35.2	Bindji/Binji	11.3 × 50.5 × 4	Insect damage – highly attenuating materials (metal mouth piece) – more than one wood species present in object

(*continued on next page*)

Table 1 (*continued*)

Object photo	Object description	Registration number	Culture	Dimensions (cm)	Impacting factor for ROI scan (shape, materials, condition)
	Staff	EO.1948.20.193	Chokwe	73.3 × 16.2 × 6.3	Large object
Musical instruments					
	Slit drum	MO.0.0.2504	Yaka	41.8 × 6.9 × 7	Insect damage
	Violin	MO.1953.74.2711	Holo	51×9.4 × 8.9	Highly attenuating materials (glass, bone and horn elements) – homogenous diameter
	Dibu bell	MO.1958.16.2	Yombe	20.1 × 12.1 × 11	Homogenous diameter
	Xylophone	MO.0.0.13352	Zande	51.8 × 8.7 × 2	Insect damage – homogenous diameter
Power objects					
	Arrow holder	EO.0.0.740-4	Luba	77.6 × 24.5 × 9.3	Large object
	Zoomorphic sculpture	EO.1962.46.4	Lega	5.6 × 19.5 × 3.5	Highly attenuating materials (bones)
	Anthropomorphic sculpture	EO.1980.2.2867	Songye	22.5 × 4.8 × 7.2	Highly attenuating materials (teeth and metal)
	Zoomorphic sculpture	EO.0.0.3659	Yombe	23×49×19	Highly attenuating materials (nails and glass)

Scans from HECTOR were reconstructed using the Octopus Reconstruction software [34], while scans from CoreTOM were reconstructed with the Panthera^{TM} software. The open-source software ImageJ [35] was used to digitally slice the reconstructed volumes in the transverse, radial and tangential direction and for quantitative measurements of the anatomical features of interest. Three-dimensional models of the scanned volumes were rendered using VGStudioMAX (Volume Graphics, Germany).

3.4. Wood identification

We followed an identification protocol similar to that of Hubau and co-authors [36]. The diagnostic anatomical features that could be distinguished on the three digital wood sections (transversal, radial and tangential) were described following the coded system drafted by the IAWA committee [37]. Each feature (given a number from 1 to 163) is described as either present (p) or absent (a). In phase 1 of the protocol, this anatomical description is entered in the search function of the online database InsideWood [38,39]. Since wood anatomical identification to the species level is only rarely possible and since not all species are included in the InsideWood database, in this first phase only the genera are being retained.

In phase 2 we expanded the results considering every species within the genera of phase 1. This large list was cross-referenced to the geographic distribution data from the RAINBIO database [40,41]. RAINBIO compiles spatially-referenced data for vascular plants across tropical continental Africa, integrating information from herbaria databases (e.g., Meise Botanic Garden) and vegetation plot inventories. We also verified species names for accuracy and taxonomic currency using the African Plant Database [42]. Comparative reference materials were then consulted, including thin sections available on InsideWood and in the Tervuren Xylarium reference collection curated by the RMCA's wood biology department [43]. This collection comprises over 81,000 wood specimens from >13,500 species, with over 20,500 thin section sets in the three principal directions [3,44]. Many species and lower taxa are represented by multiple samples from different specimens [43,45].

In the final phase of the protocol, we retained only those species that occur in the general region of the object's originating culture, as well as have either a digital or physical cross-section available for comparison. These species were evaluated based on a wide range of anatomical features to assess their similarity to the anatomy observed in the X-ray µCT scans. Species were ranked from most (most likely identification) to least visually compatible.

3.5. Properties and occurrence

After identifying the wood species for each object, we investigated the rationale behind the selection of specific tree species. To explore potential links between an object's function and the wood's material properties, we collected data on specific gravity, hardness, and durability. For the specific gravity, expressed in g/cm^3, we used the Tropical Timber Atlas [46], CIRAD [47], and the in-house Tervuren database. Information on wood and resistance to dry wood borers was drawn from DRYAD [48], CIRAD [47], and Agroforestree [49]. The geographic distribution of the identified wood species or genera on the African continent was visualized using the RAINBIO database. Abundance data, while useful for understanding species selection, remain scarce in the Congo Basin except for intensively studied sites like Yangambi in the Tshopo province. Since data are collected non-uniformly, we used RAINBIO as an approximation of geographic occurrence, rather than a proportion of the species in the forest.

4. Results

4.1. Achieved resolutions

Despite the deliberately chosen wide range of objects in terms of size, materials and shape, a reconstructed voxel size smaller than 8.5 µm was acquired for 18 of the 20 scanned heritage objects. The highest achieved resolution in this study, 3.5 µm reconstructed voxel size, was obtained for the smallest object in the selection (a statue of a kneeling figure with a width of 9.8 cm), but also for some of the largest objects. Figs. 1a, b and c show how the Chokwe staff (73 cm high), the Luluwa Mask (58 cm high) and the toy crocodile (104 cm long but made of movable parts) were positioned so the objects' smallest width was placed close to the X-ray source, while the wider parts move over or under the scanner. Fig. 1d shows the set-up for the ROI scan of the Yombe power object, which was positioned to avoid the highly attenuating metal nails and glass eyes of the sculpture. For each of the 20 objects an information sheet was made (see supplementary material). In the top left corner, a short description of the custom set-up of each object can be found.

4.2. Wood identification

The wood of all 20 Sub-Saharan African heritage objects could be identified, with two of the objects, the Bindji pipe and the Chokwe elephant sculpture, containing two different wood species. Of the 22 wood identifications, 18 could be narrowed down to species level, three were identified to genus level and one as a liana, of which we could determine a likely botanical family. Fig. 2 illustrates the annotation process of the scans, with the example of the Luluwa mask. It shows the 3D volume of the mask's internal wood structure alongside the three resliced wood planes with indications of the diagnostic anatomical features that could be distinguished for this wood species. The individual information sheet of each object contains the anatomical description, the identification steps, as well as a summary of the wood properties and occurrence on the African continent (see supplementary material).

Table 2 lists the resolutions obtained for each object, as well as the taxonomic identification and some properties of the wood: density and durability. Not enough data was available on the hardness of the wood for all of the species and as such hardness data was not included.

Fig. 3 shows the ROI scans of four objects in order to highlight the variety of diagnostic features that helped to identify the 22 identified tropical wood species. *Crossopteryx febrifuga* is characterized on the transverse plane by many small, solitary vessels. This species could be recognized at a resolution of 5 µm in the Beembe sculpture (Fig. 3a). The Lega mask (Fig. 3b), identified as *Alstonia* sp., displayed axial parenchyma in a narrow-banded pattern. This anatomical feature was only visible at the lower resolution of 14 µm reconstructed voxel size because of a consolidation treatment in the past. The substance that saturated the axial parenchyma and ray cells there now caused bright spots in the scans, making them visible on the lower resolution scans. The Luba arrow holder scan (Fig. 3c) shows vessels in a diagonal/radial pattern, as well as tyloses present in the vessels and crystal and silica inclusions in the ray cells, which helped identify the species as *Synsepalum subcordatum.* The scans of *Pterocarpus soyauxii* at 6 µm in the Zande xylophone show gums in the vessels, winged aliform and confluent parenchyma and storied rays (Fig. 3d).

5. Discussion

5.1. µCT-based wood identification

This study successfully identified the wood of all 20 scanned objects, 18 of which to species level. Both quantitative and qualitative diagnostic anatomical features could be described at the large range of resolutions as either present or not, narrowing down the potential identifications. This large dataset of 20 varied objects serves to further elaborate on smaller case studies, which demonstrated the feasibility of X-ray µCT for wood identification in heritage [27–30]. The range in resolutions (from the highest at 3.5 µm voxel size to the lowest at 20 µm voxel size) reflects the impact of the variation in sizes, shapes and materials in the selected objects.

In a previous publication we explored the potential of X-ray µCT for wood identification using reference samples, where controlled variations in resolution were possible [50]. That exploratory work indicated that a resolution range between 3 µm and 8 µm was necessary for successful identification. In this study, testing theory against practice, most of the objects conformed to these findings. However, even the four objects scanned at lower resolution yielded sufficient diagnostic features to permit wood identification. This suggests that although a resolution of 3–8 µm is ideal, the presence of large enough key anatomical features in the wood can allow for identification of certain wood species even at lower resolutions.

In terms of specific anatomical details, scalariform perforations, which are a diagnostic feature, were not visible even at 3.5 µm. In the analysis of the Chokwe staff this feature could not be used to conclusively distinguish between *Rothmannia* sp. and *Microdesmis* sp.. Other characteristics, such as fibre thickness and ray width, were used for the final identification. In our exploratory study [50], however, we found that these perforations could be distinguished at 3 µm but not at 8 µm. This difference can be in part explained by a higher signal to noise ratio found in ROI scans used in this study, rather than scanning small pieces of wood for the previous study. Crystals, another important diagnostic feature, were clearly visible, though subtle differences in brightness between crystals and silica bodies were difficult to quantify as illustrated by the

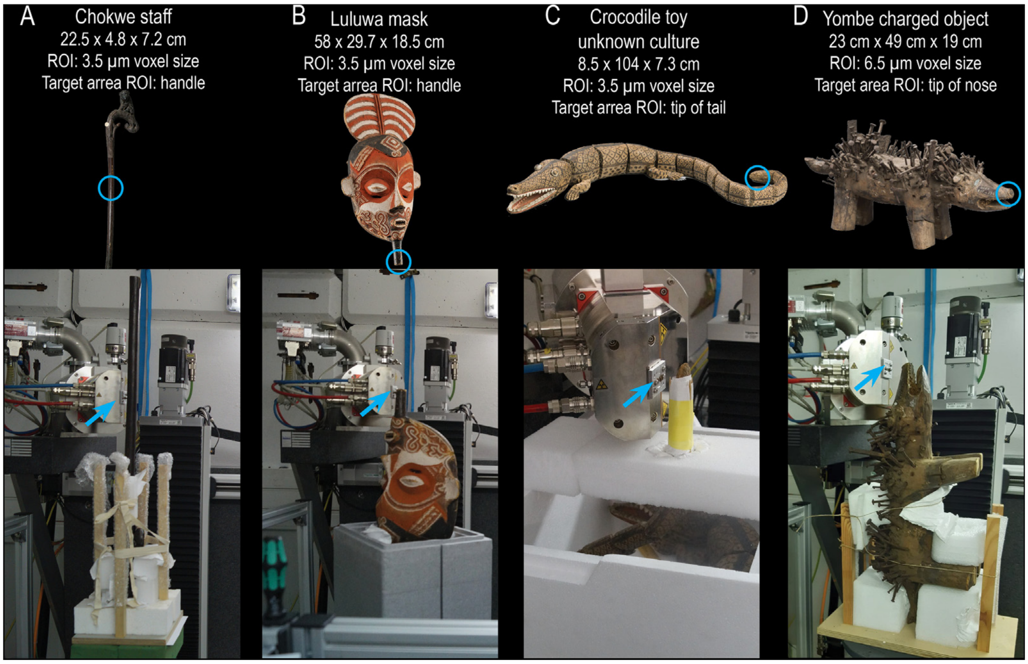


Fig. 1. Examples of object-positioning during ROI scans: the objects' narrowest part is positioned as close to the X-ray source (indicated with a blue arrow) as possible. The Chokwe staff and Luluwa mask are put upside down to target their handles. The crocodile toy is made from moveable parts and could be positioned with the tip oriented vertically (reinforced by Tyvek©, bamboo sticks and tape) and as such the body of the crocodile could move underneath the X-ray source. The zoomorphic sculpture from the Yombe culture, with glass eyes and most of its body covered in metal elements, is positioned vertically in a wooden structure so the ROI scan targets the tip of the figure's nose and avoids including the highly attenuating materials in the scan.

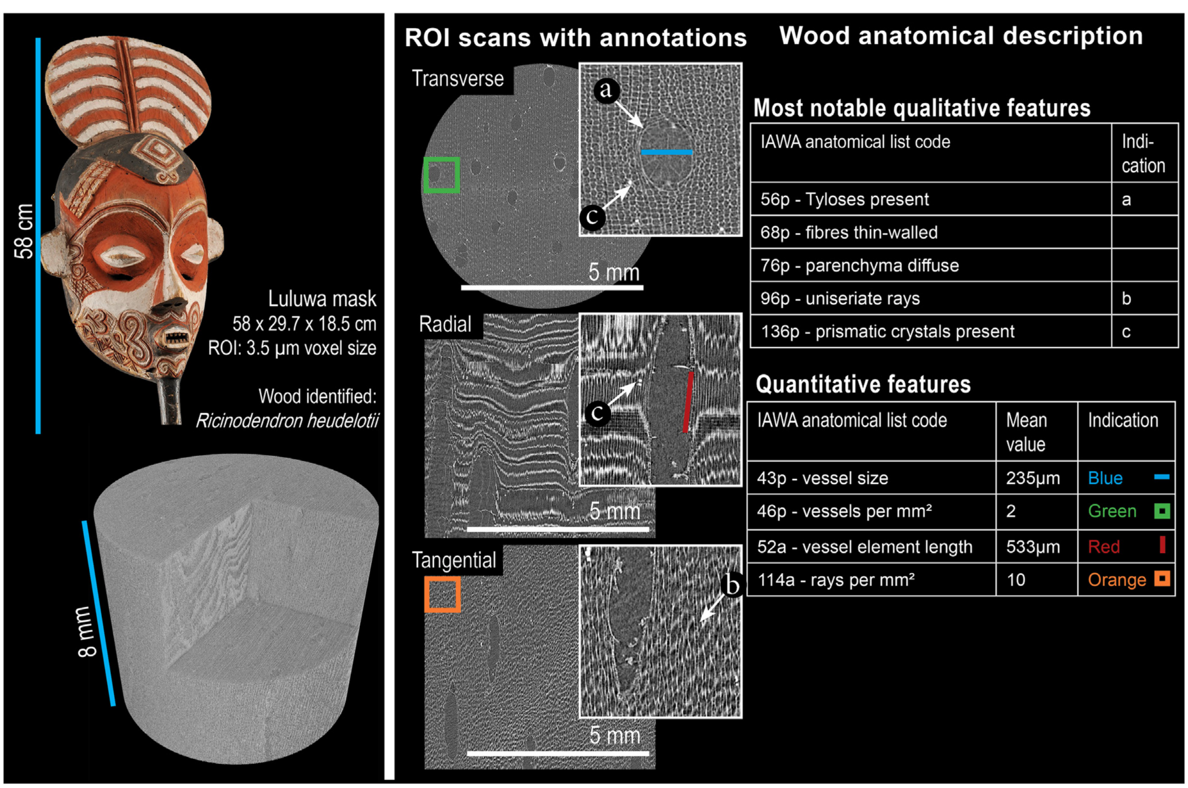
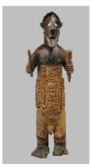
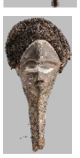
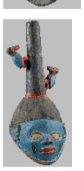


Fig. 2. Wood identification process illustrated by the Luluwa mask, identified as Ricinodendron heudelotii. The 3D rendering beneath the object photo shows the ROI scan, an 8 mm high cylinder of the internal wood structure (in the object's handle). This ROI scan was digitally resliced to show the transverse, radial and tangential directions of the wood. Annotations of most notable qualitative and quantitative features are indicated on the scans as well as described in the table on the right.

Table 2
An overview per object of the achieved resolution (reconstructed voxel size), the identified wood species and the mechanical and physical properties of the identified wood species (sources: tropicaltimber.info; cirad.tropix.fr).

Object photo	Object description	ROI resolution	Wood identification	Specific gravity (12% MC)	Resistance to dry wood borers
Sculptures					
	Kneeling Figure sculpture	4 µm	*Diospyros* sp.	0.9 g/cm³	Durable
	Beembe statue	5 µm	*Crossopteryx febrifuga* (Afzel. Ex G.Don) Benth	0.68 g/cm³	Not found
	Chokwe elephant sculpture	8 µm	Body: *Vitex doniana* Sweet Tusks: *Mitragyna stipulosa* (K.Krause) Risdale	0.4 g/cm³ 0.57 g/cm³	Not found Susceptible
	Yombe funerary statue	8.5 µm	*Ricinodendron heudelotii* (Baill.) Pierre ex Heckel	0.26 g/cm³	Susceptible
Masks					
	Luluwa mask	3.5 µm	*Ricinodendron heudelotii* (Baill.) Pierre ex Heckel	0.26 g/cm³	Susceptible
	Pende mask	6 µm	*Alstonia* sp.	0.36 g/cm³	Susceptible
	Lega mask	14 µm	*Alstonia* sp.	0.36 g/cm³	Susceptible
	Yoruba mask	7 µm	*Ricinodendron heudelotii* (Baill.) Pierre ex Heckel	0.26 g/cm³	Susceptible
Objects of use					
	Crocodile toy	4.5 µm	*Bombax brevicuspe* Sprague	0.43 g/cm³	Susceptible
	Zande knife	5 µm	*Balanites aegyptiaca* (L.) Delile var. Aegyptiaca	0.66 g/cm³	Not found
	Bindji pipe	Tank: 5 µm Bowl: 20 µm	Crf. Liana *Crossopteryx febrifuga* (Afzel. Ex G.Don) Benth	Not found 0.68 g/cm³	Not found Not found

(*continued on next page*)

Table 2 (*continued*)

Object photo	Object description	ROI resolution	Wood identification	Specific gravity (12% MC)	Resistance to dry wood borers
	Chokwe staff	3.5 µm	*Microdesmis puberula* Hook.f. ex Planch.	0.53 g/cm³	Susceptible
Musical instruments					
	Yaka slit drum	6 µm	*Markhamia tomentosa* (Benth.) K.Schum.	0.50 g/cm³	Susceptible
	Holo violin	7 µm	*Entandrophragma cylindricum* (Sprague) Sprague	0.69 g/cm³	Durable
	Yombe bell	8 µm	*Crossopteryx febrifuga* (Afzel. Ex G.Don) Benth	0.68 g/cm³	Not found
	Zande xylophone	8 µm	*Pterocarpus soyauxii* Taub.	0.79 g/cm³	Durable
Power objects					
	Luba arrow holder	6 µm	*Synsepalum subcordatum* De Wild.	0.76 g/cm³	Not found
	Lega zoomorphic sculpture	3.5 µm	*Albizia adianthifolia* (Schumach.) W.Wight	0.63 g/cm³	Durable
	Songye anthropomorphic sculpture	3.5 µm	*Cynometra hankei* Harms	0.84 g/cm³	Very durable
	Yombe zoomorphic sculpture	6.8 µm	*Canarium schweinfurthii* Eng.	0.49 g/cm³	Susceptible

Luba arrow holder in Fig. 3c. Pits could never be distinguished at any of the resolutions.

5.2. Wood selection

Identifying the wood in an object allows us to connect the object to the tree species it came from, to the carpenter who selected this species for the object's purpose, and to the intended use for the community it served. As such, certain relations with the physical and mechanical properties of the wood can be distinguished, telling a part of the story of the object. This approach has been discussed in previous studies, such as Mertz et al. [51], which highlight the relationship between wood properties and object function. Vidal et al. [8] explored wood selection for large-scale constructions, such as temples, where the mechanical properties of wood and the structural requirements were critical criteria in the selection process. We looked at specific gravity – correlating to its density and weight – and the natural durability of the wood species.

5.2.1. Sculptures

Two sculptures in this category were found to be made of wood exhibiting anatomical features in the smaller ranges described by IAWA. Both *Crossopteryx febrifuga*, found in the Beembe sculpture thought to be an ancestor effigy [52] and *Diospyros* sp., found in the small kneeling figure sculpture, have wood vessels measuring under 50 µm and 100 µm in diameter respectively. The small size of these elements facilitates a smooth finish of the wood surface, which could suggest that aesthetic factors, such as the fine grain of the wood, played a significant role in the choice of these species during the manufacturing process.

The Chokwe elephant sculpture is comprised of two different wood species. The body is made of *Vitex doniana*, and tinted a deep black by use of a patina finish. The tusks were identified as *Mytrag-*

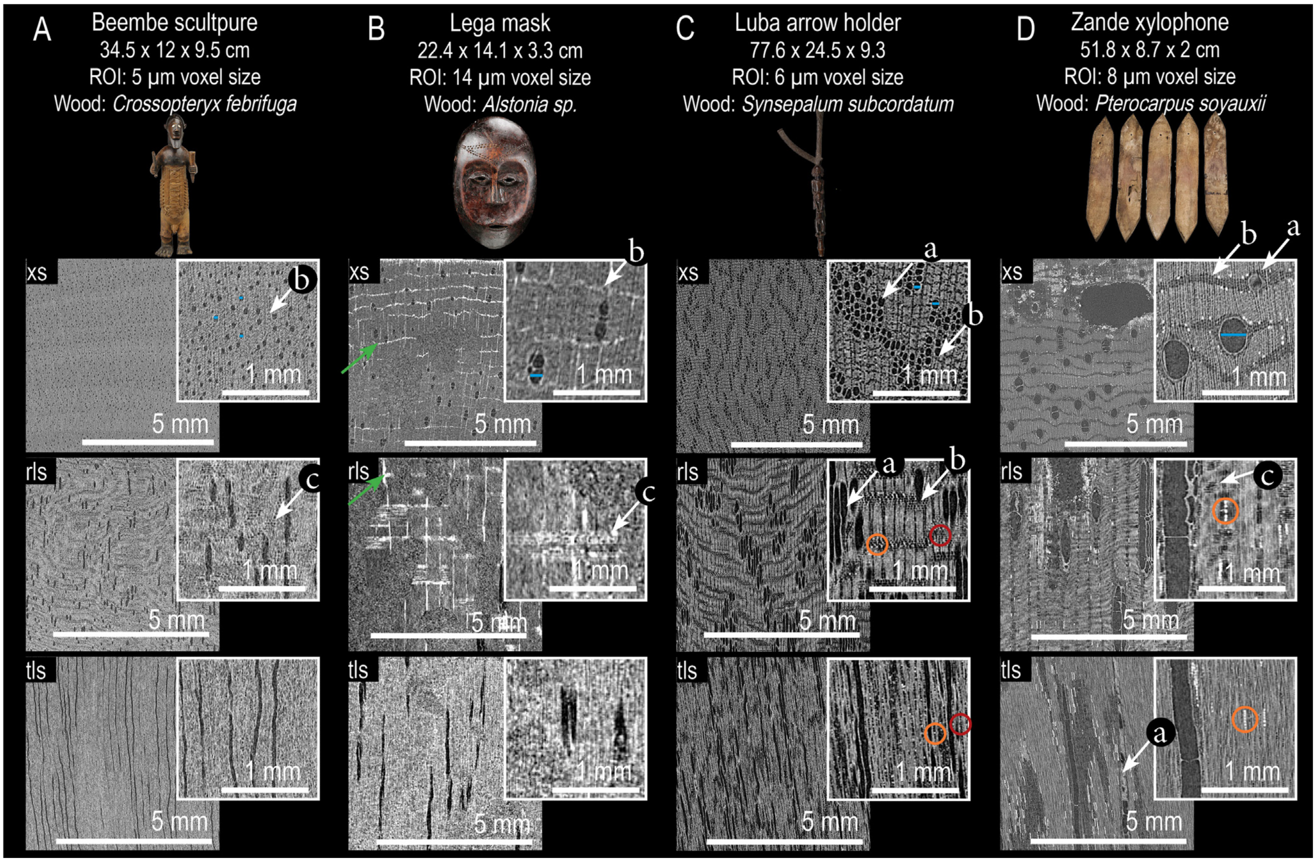


Fig. 3. Four examples of identified African objects with the reslices of the ROI scan showing the transverse (xs), radial (rls) and tangential (tls) plane. Indications show distinct wood features on each of the scans: (blue line) tangential diameter of vessel lumina; (a) deposits in the vessels; (b) axial parenchyma patterns; (c) ray cell configuration; (red circle) silica bodies (orange circle) prismatic crystals . The consolidant can be seen in the scans and is indicated with a green arrow.

yna stipulosa, with no finishing product added. Possibly the white colour of this wood was chosen to imitate ivory in this object.

In comparison, the funerary sculpture is made of *Ricinodendron heudelotii*. Its vessels exceed 200 µm in diameter, resulting in a rougher grain texture. The reason for this light-weight wood is related to its specific function. Made in the likeness of a deceased, the sculpture was displayed in an outdoor monument. After a number of years, it would decay and disappear as intended [53,54]. *Ricinodendron heudelotii*, susceptible to insect and fungal attacks, thus with low durability, corresponds to the use of the object as found in literature: to disappear [52].

Crossopteryx febrifuga and *Ricinodendron heudelotii* are both widely available in many regions in Central Africa, making it an accessible and practical choice for object construction [39,40]. It is important to note that only one object in this study was identified as a species listed under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES): *Diospyros* sp. This information has implications for the museum's international loan and exhibition policies.

5.2.2. Masks

A clear connection emerges between the specific gravity of the wood and the weight of the masks. Of the four analysed masks, two were made from *Ricinodendron heudelotii*, which has a specific gravity of $0.26 g/cm^3$, and two made from a species of the genus *Alstonia*, with a specific gravity of approximately $0.36 g/cm^3$. In cultures like the Yaka and Chokwe masks are an integral part in coming-of-age ceremonies. The lightweight nature and low durability of both these two woods is directly related to the function of the masks, as they were often carved to be worn, and danced in, at a singular occasion [55–57]. The choice of *Ricinodendron heudelotii* and *Alstonia* sp. thus reflects both practical and functional considerations in mask-making.

In addition to their light-weight properties, both genera are commonly present where these masks were produced, making them readily accessible materials for mask-makers. The trees are also of sufficient size to allow for the carving of larger objects, further supporting their use in the creation of ceremonial masks. This suggests that abundance and local availability of the wood were important factors influencing material selection for these [39,40].

5.2.3. Objects of use

The objects in this category exhibit a wide range of specific functions, making it challenging to establish a unifying criterion. The wood of the Zande knife handle was identified as *Balanites aegyptiaca,* and the intricately carved Chokwe staff as *Microdesmis puberula*. The use of both objects suggests the wood was supposed withstand some pressures in daily use, which can correspond to the relatively high density of both identified wood species.

The Bindji pipe contains two wood species, creating a contrast in texture. The rough-grained stem, identified as a liana from the Combretaceae family [58], features large vessels and a natural hollow core, which provides a conduit for smoke. The decorative components of the object, mouthpiece and bowl, were carved from *Crossopteryx febrifuga*, allowing intricate carvings and a smooth finish. This reinforces the idea that aesthetic considerations may have played a role in material selection. Literature also suggests the heat resistance properties of *Crossopteryx febrifuga* were important aspects in the manufacturing of a pipe, but we could not find enough information on the wood properties to confirm this [59]. Finally, the wood from the toy crocodile was identified as *Bombax brevicuspe.* The lightweight wood can be linked to the object's intended use, allowing each moveable part—held together by plant-fiber string—to be easily handled.

5.2.4. Musical instruments

The analysis of the four musical instruments showed the use of distinct wood species, with two of these linked to acoustic qualities as described in literature. The identification of *Pterocarpus soyauxii* (African Padouk) in two of the instruments is consistent with its documented high density, durability, and favourable acoustic properties, such as high elasticity modulus and low internal friction. These qualities are vital for percussion instruments, supporting their resonance and tonal clarity [60–63].

One instrument, a violin, was identified as being made from *Entandrophragma cylindricum*. This species is used in modern acoustic guitars, where its wood contributes to sound quality by forming part of the sound chamber [64]. The soundboard of the violin was found to be a Monocotyledon. This is a very low density material, which is common for soundboards in string instruments [65].

For the other two instruments— a small slit drum made of *Markhamia tomentosa* and a Yombe bell crafted from *Crossopteryx febrifuga*—there is no literature addressing these species' acoustic properties. This specific Yombe bell is mainly noted in literature for its intricate carvings and use in ceremonies, not for its sound [66–68]. Again, the smooth grain of *Crossopteryx febrifuga* likely played a significant role in its selection, emphasizing the dual importance of aesthetic and functional qualities in the choice of wood.

5.2.5. Power objects

The objects in this category are highly varied in their functions, ranging from personal to communal use. Their unifying characteristic lies in their connection to the spirit world. While the woodcarver was responsible for shaping these objects, they didn't become imbued with power until they were activated through the involvement of an *Nganga* (ritual specialist or healer). There is limited literature regarding whether the choice of wood was as critical to the objects' spiritual function as other aspects of their creation. It is important to acknowledge that the spiritual meanings associated with specific tree species are part of the privileged knowledge inherent to the communities that created and used these objects [69,70]. While it is certain that the selection of wood species held significance in the creation and activation of these objects, understanding why particular species were chosen remains a complex question that can only be answered through further culturally-informed research. The sacred nature of this knowledge, strongly rooted in the communities' worldviews, limits the extent to which external researchers can fully interpret these choices [71,72].

6. Conclusion

This study demonstrates the successful application of X-ray micro-tomography (μCT) for the non-destructive wood identification of 20 Sub-Saharan African heritage objects, representing a wide range of sizes, shapes, materials, and conditions. Based on the scans, 18 of 22 wood species present in the 20 cultural objects could be identified to species level, 3 could be identified to genus level and lastly, the stem of the Bindji pipe was identified as a liana, probably of the Combretaceae family. The distribution, diameter, and density of the vessels proved to be highly diagnostic, allowing for an accurate identification of species such as *Crossopteryx febrifuga* and *Ricinodendron heudelotii* at various resolutions. The presence of tyloses and other vessel deposits further supported species identification, while distinct axial parenchyma patterns and the visibility of rays and inclusions, such as prismatic crystals and silica bodies, provided additional confirmation of wood species. The ability to observe these features at even lower resolutions underscores the versatility of μCT scanning as a non-invasive tool for wood identification in cultural heritage objects, providing invaluable insight into the materials used in their construction.

By correlating the identified wood species with their technical properties—such as density, and durability—we revealed significant connections between the material choices and the intended use or cultural function of the objects. This study aims to validate X-ray μCT as a powerful tool for non-invasive wood identification in heritage objects but also sheds light on the culturally and functionally informed selection of wood species in African material culture. These findings enrich our understanding of the technical knowledge and craftsmanship behind the creation of these objects, while providing crucial insights for their conservation and preservation in museum collections.

Ethical considerations

This research is based on Western methodologies and interpretations of African cultural objects. We acknowledge that, as European researchers, we cannot fully grasp all aspects and meanings of these objects. We have been guided in the disclosure of the results by the framework provided by source community contacts, and our objective is limited to uncovering certain elements of their (material) context. We are committed to supporting researchers from the source communities by providing them with the scans and results collected in this study.

Acknowledgments

The authors acknowledge the financial support of the Belgian Science Policy Office (BELSPO) for the TOCOWO project and the CONteXT project (B2/191/p2/TOCOWO; B2/233/P2/CONteXT tocowo.ugent.be). We also acknowledge the financial support by the BOF Special Research Fund for the UGCT Core Facility (BOF.COR.2022.008) and for the Nanowood CT system (BOF Starting Grant JVdB, BOFSTG2018000701, FWO Grant G00972ON, G019521 N and FBW-CWO-UGent grant JVdB). W.H. received support from BELSPO through research profile FED-tWIN2019-prf-075 (CongoFORCE).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.culher.2025.03.001.

References

[1] M. Dominguez-Delmas, A. Daly, K. Haneca, From forest to heritage: unravelling the journey of historical timbers and wooden cultural heritage, International Journal of Wood Culture 1 (3) (2023) 1–7, doi:10.1163/27723194-bja10024.
[2] A. Lo Monaco, F. Balletti, C. Pelosi, Wood in cultural heritage properties and conservation of historical wooden artefacts, European Journal of Science and Technology 14 (2) (2018) 161–171 http://hdl.handle.net/2067/48001.
[3] H. Beeckman, Collections of the RMCA: wood, Museum series (2007) 94–95.
[4] A.N. Shugar, B.L. Drake, G. Kelley, Rapid identification of wood species using XRF and neural network machine learning, Science Rep 11 (1) (2021) 1–10, doi:10.1038/s41598-021-96850-2.
[5] P. Ravindran, A.C. Wiedenhoeft, Comparison of two forensic wood identification technologies for ten Meliaceae woods: computer vision versus mass spectroscopy, Wood Science Technology 46 (2) (2020) 1163–1175, doi:10.1007/s00226-020-01178-1.
[6] M.C. Timar, L. GurĂu, M. Porojan, Wood species identification, a challenge of scientific conservation, International Journal of Conservation Science 3 (1) (2012) 11.
[7] J.C. Ferreira de Melo Junior, M.R. Torres Boeger, The use of wood in cultural objects in 19th century southern Brazil, IAWA Journal 36 (1) (2015) 98–116, doi:10.1163/22941932-00000088a.
[8] N. Romero Vidal, The journey of Nudsugana: a multidisciplinary study of wooden sculptures of Gunayala (Panama) at the Världskulturmuseet in

Gothenburg (Sweden), International Journal of Wood Culture 3 (2023) 224–248, doi:10.1163/27723194-bja10020.

[9] M. Grabner, Werkholz: Eigenschaften Und Historische Nutzung 60 Mitteleuropäischer Baum und Straucharten, Verlag Dr, Kessel, Remagen, 2017.

[10] J. da Silva, R. Bordalo, J. Pissarra, Wood identification: an overview of current and past methods, Estudos de Conservacao e Restauro 12 (12) (2022) 45–68, doi:10.34632/ecr.2020.10680.

[11] C. Cartwright, The principles, procedures, and pitfalls in identifying archaeological and historical wood samples, Annals of Botany 116 (1) (2015) 1–13, doi:10.1093/aob/mcv056.

[12] M.C. Low, N. Schmitz, L.E. Boeschoten, J.A. Cabezas, M. Cramm, V. Haag, et al., Tracing the world's timber: the status of scientific verification technologies for species and origin identification, IAWA Journal 0 (0) (2022) 1–22, doi:10.1163/22941932-bja10097.

[13] L. Akhmetzyanov, A. Buras, U. Sass-Klaassen, J. Ouden, G. Mohren, P. Groenendijk, et al., Multi-variable approach pinpoints origin of oak wood with higher precision, Journal Biogeogr. 46 (1) (2019) 1–15, doi:10.1111/jbi.13576.

[14] L. Jiao, Y. Lu, T. He, J. Li, Y. Yin, A strategy for developing high-resolution DNA barcodes for species discrimination of wood specimens using the complete chloroplast genome of three *pterocarpus* species, Planta 250 (1) (2019) 95–104, doi:10.1007/s00425-019-03150-1.

[15] P. Brunswick, D. Cuthbertson, J. Yan, C.C. Chua, I. Duchesne, N. Isabel, et al., A practical study of CITES wood species identification by untargeted DART/QTOF, GC/QTOF and LC/QTOF together with machine learning processes and statistical analysis, Environmental Advances 5 (1) (2021) 1–10, doi:10.1016/j.envadv.2021.100089.

[16] Deklerck, V., Lancaster, C.A., Van Acker, J., Espinoza, E.O., Van den Bulcke, J., Beeckman, H. (2020). Chemical fingerprinting of wood sampled along a pith-to-bark gradient for individual comparison and provenance identification forests (11(1): 107–120, https://doi.org/10.3390/f11010107

[17] K.E. Duncan, K.J. Czymmek, N. Jiang, A.C. Thies, C.N. Topp, X-ray microscopy enables multiscale high-resolution 3D imaging of plant cells, tissues, and organs, Plant Physiology 188 (2) (2022) 831–845, doi:10.1093/plphys/kiab405.

[18] J. Van den Bulcke, M. Boone, J. Van Acker, M. Stevens, L. Van Hoorebeke, X-ray tomography as a tool for detailed anatomical analysis, Annals of forest science 66 (1) (2009) 508–520, doi:10.1051/forest/2009033.

[19] K. Steppe, V. Cnudde, C. Girard, R. Lemeur, J.-P. Cnudde, P. Jacobs, Use of X-ray computed microtomography for non-invasive determination of wood anatomical characteristics, Journal of structural biology 148 (2004) 11–21, doi:10.1016/j.jsb.2004.05.001.

[20] S.-W. Hwang, S. Tazuru, J. Sugiyama, Wood identification of historical architecture in Korea by synchrotron X-ray microtomography-based three-dimensional microstructural imaging, Journal of the Korean Wood Science and Technology 48 (3) (2020) 283–290, doi:10.5658/WOOD.2020.48.3.283.

[21] S. Tazuru, J. Sugiyama, Wood identification of Japanese Shinto deity statues in Matsunootaisha Shrine in Kyoto by synchrotron X-ray microtomography and conventional microscopy methods, Journal of wood science 65 (1) (2019) 1–7, doi:10.1186/s10086-019-1840-2.

[22] S. Mizuno, R. Torizu, J. Sugiyama, Wood identification of a wooden mask using synchrotron X-ray microtomography, Journal of archaeological science 37 (2010) 2842–2845, doi:10.1016/j.jas.2010.06.022.

[23] T. Trojek, A. Duskova, Quantitative X-ray fluorescence micro-analysis of wood samples and visualisation of tree rings, Radiation Physics and Chemistry 218 (1) (2024) 111603, doi:10.1016/j.radphyschem.2024.111603.

[24] H.S. Rocha, J.W. Batista Braga, D.C.G.C. Kunze, V.T. Rauber Coradin, T.C. Monteiro Pastore, Identification of mahogany sliced veneer using handheld near-infrared spectroscopy device and multivariate data analysis, IAWA Journal 42 (3) (2021) 1–12, doi:10.1163/22941932-bja10054.

[25] F. Snel, J.W. Batista Braga, D.C. da Silva, A.C. Wiederhoeft, A. Costa, R. Soares, et al., Potential filed-deployable NIRS identification of seven *Dalbergia* species listed by CITES, Wood Science and Technology 52 (2018) 1411–1427.

[26] J.W. Batista Braga, NIRS identification of *Swietenia macrophylla* is robust across specimens from 27 countries, IAWA Journal 37 (3) (2016) 420–430, doi:10.1163/22941932-20160144.

[27] K. Rankin, Z. Hazell, A. Middleton, M. Mavrogordato, Micro-focus X-ray CT scanning of two rare wooden objects from the wreck of the London and its application in heritage science and conservation, Journal of archaeological science 39 (1) (2021) 103158, doi:10.1016/j.jasrep.2021.103158.

[28] K. Kobayashi, S.-H. Hwang, T. Okochi, W.-H. Lee, J. Sugiyama, Non-destructive method for wood identification using conventional X-ray computed tomography data, Journal of cultural heritage 38 (1) (2019) 88–93.

[29] M. Fioravanti, G. Di Giulio, G. Signorini, A non-invasive approach to identifying wood species in historical musical instruments, Journal of cultural heritage 27 (2017) 70–77, doi:10.1016/j.culher.2016.05.012.

[30] K. Haneca, K. Deforce, M.N. Boone, D. Van Loo, M. Dierick, J. Van Acker, et al., X-ray sub-micron tomography as a tool for the study of archaeological wood preserved through the corrosion of metal objects, Archaeometry 54 (5) (2011) 893–905, doi:10.1111/j.1475-4754.2011.00640.x.

[31] M. Hoffman, Repatriation: the limits of museum's' archives, in: C. Deussen, Y. Karakis (Eds.), Thinking About the Archive & Provenance Research, 4, 2022, pp. 28–33 https://www.proveana.de/en/link/lit00005370.

[32] UGent Centre for X-ray tomography. www.ugct.ugent.be. Accessed 15 January 2025.

[33] B. Masschaele, M. Dierick, D. Van Loo, J. Van den Bulcke, J. Van Acker, V. Cnudde, L. Van Hoorebeke, Recent micro-CT scanner developments at UGCT, Nuclear Instruments and Methods in Physics Research 324 (2013) 35–40, doi:10.1016/j.nimb.2013.10.051.

[34] J. Vlassenbroeck, V. Cnudde, B. Masschaele, M. Dierick, L. Van Hoorebeke, P. Jacobs, A comparative and critical study of X-ray CT and neuron CT as non-destructive material evaluation techniques, Geological Society London Special Publications 271 (2006) 277–285, doi:10.1144/GSL.SP.2007.271.01.26.

[35] J. Schindelin, I. Arganda-Carreras, E. Frise, V. Kaynig, M. Longair, T. Pietzsch, et al., Fiji: an open-source platform for biological-image analysis, Nature methods 9 (2012) 676–682, doi:10.1038/nmeth.2019.

[36] W. Hubau, J. Van den Bulcke, P. Kitin, F. Mees, J. Van Acker, H. Beeckman, Charcoal identification in species-rich biomes: a protocol for Central Africa optimised for the Mayumbe forest, Review of Palaeobotany and Palynology 171 (2012) 164–178, doi:10.1016/j.revpalbo.2011.11.002.

[37] E. Wheeler, P. Baas, P. Gasson, IAWA list of microscopic features for hardwood identification, IAWA Journal 10 (3) (1989) 219–332.

[38] E. Wheeler, Inside Wood – A web resource for hardwood anatomy, IAWA Journal 32 (2011) 199–211, doi:10.1163/22941932-90000051.

[39] Inside Wood online database. www.insidewood.lib.ncsu.edu. Accessed 15 January 2025.

[40] Website of RAINBIO GROUP. rainbio.cesab.org. Accessed 15 January 2025.

[41] G. Dauby, R. Zaiss, A. Blach-Overgaard, L. Catarino, T. Damen, V. Deblauwe, et al., RAINBIO: a mega-database of tropical African vascular plants distributions, PhytoKeys 74 (2016) 1–18, doi:10.3897/phytokeys.74.9723.

[42] African Plant Database. www.africanplantdatabase.ch. Accessed 15 January 2025.

[43] Tervuren Xylarium Wood Database.www.africamuseum.be/nl/research/collections_libraries/biology/collections/xylarium. Accessed 15 January 2025.

[44] R. De Blaere, K. Lievens, D. Van Hassel, V. Deklerck, T. De Mil, W. Hubau, et al., SmartWoodID - an image collection of large end-grain surfaces to support wood identification systems, Database 2023 (1) (2023) 1–12, doi:10.1093/database/baad034.

[45] V. Deklerck, National treasure: Valorisation of the Federal Xylarium in Belgium for Timber Identification and Wood Technology, Ghent University, Faculty of Bioscience Engineering, 2019 http://hdl.handle.net/1854/LU-8635546.

[46] Tropical Timbers – Lesser used species. tropicaltimber.info. Accessed 15 January 2015.

[47] Tropix 7 the main technological characteristics of 245 tropical wood species. www.tropix.cirad.fr/en. Accessed 15 January 2015.

[48] DRYAD. www.datadryad.org/stash. Accessed 15 January 2015.

[49] CIFOR/World Agroforestry. www.cifor-icraf.org/. Accessed 15 January 2015.

[50] S. Dierickx, S. Genbrugge, H. Beeckman, W. Hubau, P. Kibleur, J. Van den Bulcke, Non-destructive wood identification using X-ray µct scanning: which resolution do we need? Plant Methods 20 (98) (2024) 1–14, doi:10.1186/s13007-024-01216-0.

[51] M. Mertz, S. Gupta, Y. Hirako, P. de Azevedo, J. Sugiyama, Wood selection of ancient temples in the Sikkim Himalayas, IAWA Journal 35 (4) (2014) 444–461, doi:10.1163/22941932-000000770.

[52] J. Volper, Death the root, art the flower: overview of former cultural and artistic practices in Central Africa, Ligabue Magazine XXXVII (2018) 38–75 N°72& 176.

[53] M.L. Felix, Ritual Figures in Congo, Ethnic Art and Culture Limited, Hong Kong, 2018.

[54] H. Deleval, Les Tribus Kavati du Mayombe: Notes Ethnographiques, Vromant & Co, Brussels, 1913.

[55] N. Batulukisi, 100 x Congo: Um siècle D'art Congolais à Anvers, Ed. Fagne, C, 2020.

[56] P.M. Mantuba-Ngoma, 100 x Congo: Um siècle D'art Congolais à Anvers, C. Fagne (Ed.), 2020.

[57] Kubik, G. Treasures from the Africamuseum, Tervuren. Africamuseum, Tervuren.

[58] P. Acevedo-Rodriguez, Guide to the Genera of Lianas and Climbing Plants in the Neotropics, Smithsonian Institution, Washington, 2020.

[59] R. Dechamps, Première note concernant l'identification anatomique de bois utilisés pour des sculptures en Afrique, Published in Africa-Tervuren 28 (3) (1970) 37–41.

[60] V. Bucur, Accoustics of Wood, Springer Series in Wood Science, 2006.

[61] A. Straze, B. Mitkovski, J. Tippner, K. Cufar, Z. Gorisek, Structural and acoustic properties of African padouk (Pterocarpus soyauxii) wood for xylophones, European Journal of Wood and Wood Products 73 (2015) 235–243, doi:10.1007/s00107-015-0878-0.

[62] L. Brancheriau, H. Baillères, P. Détienne, R. Kronland, B. Metzger, Classifying xylophone bar materials by perceptual, signal processing, and wood anatomy analysis, Annals for Science 63 (1) (2006) 73–81, doi:10.1051/forest:2005099.

[63] R. Dechamps, Comprendre l'anatomie du bois: étude descriptive du xylème des végétaux angiospermes dicotylédonés, Centre National D'informations Techniques Sur Le Bois, Brussels, 1971.

[64] S. Calvano, F. Negro, F. Ruffinatto, D. Zanuttini-Frank, R. Zanutiini, Use and sustainability of wood in acoustic guitars: an overview based on the global market, Heliyon 9 (4) (2023) 1–15, doi:10.1016/j.heliyon.2023.

[65] I. Brémaud, Acoustical properties of wood in string instruments soundboards and tuned idiophones: biological and cultural diversity, Journal of the Acoustical Society of America 131 (1) (2012) 807–818, doi:10.1121/1.3651233.

[66] W. MacGaffey, Treasures from the Africamuseum, Africamuseum, Tervuren, Tervuren., 1995.

[67] J. Gansemans, Collecties van het KMMA, Muziekinstrumenten, AfricaMuseum, TervurenAfricamuseum, Tervuren, 2008.

[68] S. Cooksey, R. Poynor, H. Vanhee, C.S. Forbes, Kongo Across the Waters, University Press of Florida, Gainesville, 2014.
[69] J. Volper, Présentation de quelques nkidh des Yanzi, in: Musée du Quai Branly (Ed.), La Part de l'Ombre: Sculptures Du Sud-Ouest du Congo, Skira, Paris, 2021.
[70] D. Hersak, Reviewing power, process and statement: the case of Songye figures, African Arts 43 (2) (2010) 38–51, doi:10.1162/afar.2010.43.2.38.
[71] R. O'Hern, E. Pearlstein, S.E. Gagliardi, Beyond the surface: where cultural contexts and scientific analysis meet in museum conservation of West African power association helmet masks, Museum Anthropology 39 (1) (2016) 70–86, doi:10.1111/muan.12102.
[72] M. Nooter, Secrecy: african art that conceals and reveals, African Arts 26 (1) (1993) 55–102.