Monnoye *et al. Annals of Forest Science* (2025) 82:44
https://doi.org/10.1186/s13595-025-01317-3

Annals of Forest Science

RESEARCH

Open Access

Combining wood anatomy and chemical fingerprinting maximizes tropical timber identification success

Michael Monnoye[1,2*], Mbusa Wasukundi[3,4,5], Nils Bourland[1], Ruben De Blaere[1,2], Victor Deklerck[6], Tom De Mil[3], Maaike De Ridder[1], Wannes Hubau[1,2], Félix Laurent[1], Kévin Liévens[1], Nestor Luambua[2,7], Jan Van den Bulcke[2] and Hans Beeckman[1]

Abstract

Key message A combination approach to wood identification methods yields superior results when identifying timber originating from the Central African tropics. This is demonstrated by the performance of DART-TOFMS as a fine-tuning step after the microscopic analysis of wood anatomy. These identifications reveal species misdeclarations in small-scale timber markets in the Democratic Republic of the Congo with detrimental ecological and socio-economic effects.

Context Identifying timber helps enforce international timber regulations. Both the conventional method of microscopic analysis of wood anatomy and chemical fingerprinting using Direct Analysis in Real-Time – Time-of-Flight Mass Spectrometry (DART-TOFMS) face challenges that make identifications difficult, especially in the central African tropics. Meanwhile, these methods are of immense value to help monitor forest exploitation and screen species declarations on the pivotal small-scale timber markets of the Democratic Republic of the Congo (DRC).

Aims We evaluated the performance of both wood anatomy and chemical fingerprinting to identify timber traded on local markets in the DRC and quantified the misdeclarations uncovered through these methods.

Methods We examined wood anatomy using light microscopy and performed chemical fingerprinting using DART-TOFMS for 115 timber samples originating from local markets in Kisangani, DRC.

Results Microscopic analysis of wood anatomy performed better than DART-TOFMS (41 vs. 32 species identifications), but the performance can be improved significantly by combining both techniques (56 species identifications). Our identifications revealed that 26 samples were mislabelled.

Conclusion We recommend expanding the DART-TOFMS reference databases and recognizing the power of combining established and emerging identification methods. This will help expose misdeclarations in timber markets and ultimately halt the illegal timber trade.

Keywords Microscopy, DART-TOFMS, Democratic Republic of the Congo, Illegal logging, Local markets

Handling editor: Erwin Dreyer

*Correspondence:
Michael Monnoye
michael.monnoye@africamuseum.be
Full list of author information is available at the end of the article

1 Introduction

Timber identifications reveal species misdeclarations in trade and help enforce international timber regulations. Species information is required to comply with, for instance, the Convention on the International Trade in Endangered Species (CITES), the Lacey Act, Forest Law Enforcement, Governance and Trade (FLEGT), and the European Timber Regulation (EUTR), currently transitioning to the European Deforestation Regulation (EUDR). Furthermore, wood identifications allow for better monitoring of forest resources by pinpointing the species of the timber volumes extracted during management operations (Stäuble et al. 2023). This may reveal discrepancies between forest management plans and the actual harvest or indicate species that are under heavy pressure from unregulated forest exploitation. In addition, species information is required to correctly apply wood processing methods such as drying (Wheeler and Baas 1998). As trees are usually identified in the field by their local or commercial name, this can be considered an accessible way of discerning the species of harvested timber. However, these vernacular names are ambiguous and blindly relying on them leads to false declarations (Wilkie and Saridan 1999; Brearley et al. 2019). These risks necessitate the use of reliable methods to perform botanical species identifications.

Microscopic analysis of wood anatomy is the most well-established identification method in which cell size, shape, properties and arrangement in tissues in a timber sample is scrutinized. It relies on characteristic features which can be recognized on the macroscopic or microscopic level. The standardized and mostly qualitative feature descriptions published by the International Association of Wood Anatomists (IAWA) are commonly used in conjunction with online databases and reference xylaria for routine identification (Wheeler et al. 1991; Beeckman 2003; Baas et al. 2004; Wheeler 2011; Hubau et al. 2012). Combining this with quantitative data on vessel, ray/axial parenchyma and fibre features may improve the results (He et al. 2020). While this method is mostly sufficient for identifying the genus, species-level identifications remain challenging for the many genera with little variation in wood anatomical features (Miller and Cahow 1989; Gasson 2011; Schmitz et al. 2020). This triggered an international quest for innovative techniques that may help speed up and improve wood identification (Gasson 2011), each with their own advantages, disadvantages and costs (Dormontt et al. 2015; Schmitz et al. 2020).

Chemical fingerprinting by Direct Analysis in Real Time – Time-of-Flight Mass Spectrometry (DART-TOFMS) is one such novel method, which ionizes the phytochemicals constituting the heartwood metabolome and subsequently detects their mass over charge (m/z) ratio. Wood genera or even species within genera can be characterized by differences in the presence and relative quantities of key m/z values in their metabolome profiles. Spectra from unknown timber samples can be compared either visually or through multivariate statistical analysis with a reference database, for which the Forensic Spectra of Trees (ForeST©) Database, developed by the National Fish and Wildlife Forensic Laboratory in Ashland, USA, is commonly used (Price et al. 2022). DART-TOFMS is proven to be a fast, accurate and reproducible process to identify wood at the species level for various timbers (Cody et al. 2005; Espinoza et al. 2015; Deklerck et al. 2017, 2019; Evans et al. 2017; Kitin et al. 2021; Price et al. 2022). However, this method is limited when encountering samples with external contamination, sapwood, species with similar metabolome profiles or species not yet included in the reference libraries (Deklerck et al. 2019; Price et al. 2022).

Identifications up to species level are especially tedious for timber from species-rich areas such as the central African tropics. At the same time, tropical forests are increasingly recognized for their indispensable global ecosystem services and are therefore protected under strong international laws, requiring more intense screening of timber trade markets than ever before. Central African countries currently experience an explosion in forest degradation and deforestation through exponential demographic growth combined with a strong tradition of smallholder activities (Gerland et al. 2014; Tyukavina et al. 2018). The Democratic Republic of Congo (DRC) stands out in this context, since it harbours around half of Africa's tropical rainforests and approximately 90% of its timber harvest happens through small-scale chainsaw logging, of which ca. 85% is supplied to the domestic market (Lawson 2014; Lescuyer et al. 2014). Concurrently, small-scale operators mostly disregard whether wood is of legal origin: studies mention numbers as high as 96% lacking a logging permit (Lawson (2014); Lescuyer et al. 2014). The aforementioned identification methods could be of immense value to help monitor forest exploitation and screen timber (mis)declarations on the rapidly emerging but under-researched local timber markets.

Therefore, the main objectives of this paper are (i) to evaluate the performance of both the conventional wood anatomy method and the DART-TOFMS chemical fingerprinting method in identifying timber traded on local markets in the DRC and (ii) to quantify the level of species misdeclarations on these markets. To do so, we collected samples of Central African timber from the small-scale timber markets in the Kisangani area (DRC). We quantified how many samples can be identified up to genus and species level, using each method individually as well as in combination. We used the resulting identifications of the samples to verify the accuracy of the species declarations under which the timber was marketed.

2 Material and methods

2.1 Sampling

We gathered a set of 115 timber samples from local markets and sawmills in the city of Kisangani (0°31′N, 25°11′E), located in the province of Tshopo, DRC. This region is in the heart of the wet tropical biome of Central Africa, listed as Af in the Köppen classification (Peel et al. 2007). The timber samples were sold under vernacular names; these declarations were translated to botanical names using literature on forests in the Kisangani region in combination with the input of botanists from INERA-Yangambi (Tailfer 1989; Lejoly et al. 2010; DIAF 2017). Each sample was given a code based on the Tervuren wood (Tw) collection (Beeckman 2003).

2.2 Identification through microscopic analysis of wood anatomy

Microsections of the samples were prepared using internationally accepted procedures (Schmitz 2010; Gärtner and Schweingruber 2013). Subsamples of ca. 1 cm^3 were separated and softened in a mix of glycerol and demineralized water (1:4) in an oven at 60 °C. Samples originating from denser wood were further softened in a pressure cooker. We made microsections of the transversal (XS), tangential longitudinal (TLS) and radial longitudinal (RLS) planes using a Microm HM 440 E semi-automatic sliding microtome. The sections were dyed using an aqueous safranine and alcian blue solution, dehydrated using a four-step ethanol dilution series and mounted in Euparal. We used an Olympus BX50 optical microscope to observe the anatomical features of the microsections.

Microscopic analysis of wood anatomy resulted in a string of IAWA features for each sample (Wheeler et al. 1989). Our identification protocol is based on that of Hubau et al. (2012). The protocol starts by entering the anatomical description in the search function of the online database InsideWood, which returns a list of matching species. Although this database contains anatomical descriptions of over 7.000 modern hardwood species, it is not complete (Wheeler 2011). Specifically, species-rich genera are often represented by only a few species. We therefore enriched the InsideWood query result by adding all species from the genera, using checklists from online taxonomic databases: Plants of the World Online (POWO (POWO 2025)), Global Biodiversity Information Facility (GBIF.org 2025), World Flora Online (WFO 2025), and African Plant Database (African Plant Database 2025). We then refined the results using the geographic distribution data from these databases, retaining only species that may occur in the DRC. The protocol ends with a comparative microscopy phase where the wood anatomy of the microsections of a sample is compared with the wood anatomy of microsections in the Tervuren Xylarium reference collection curated by the Royal Museum for Central Africa's wood biology department. This collection comprises over 81 000 wood specimens from more than 13 500 species, with over 20 500 microsection sets in the three planes of reference (XS, TLS, RLS) (Beeckman 2003; De Blaere et al. 2023).

2.3 Identification through chemical fingerprinting using DART-TOFMS

We separated heartwood slivers (ca. 2 cm) for chemical analysis with DART-TOFMS. The measurements were performed with a JEOL JMS-T100LP AccuTOF LC-plus 4G time-of-flight mass spectrometer with an IonSense DART-JS SVP ionization source using the msAxel software package. The mass spectrometer settings were as follows: positive ion mode, orifice 1 temperature at 120 °C, detector voltage at 2400 V, orifice 1 voltage at 30 V, ring lens voltage at 5 V, orifice 2 voltage at 5 V, ion guide RF voltage at 800 V, ion guide bias at 27 V, focus lens voltage at −120 V, reflectron voltage at 980 V, push voltage at 777.8 V, pull voltage at − 777.8 V, suppress voltage at 0.20 V, flight tube voltage at − 7000 V. The slivers were held in a He gas stream at 350 °C with spectrum measurements at 1 recording per 0.4 s. Spectra were gathered in single runs of 15 min with drift compensation, with a poly-ethylene glycol 600 calibration every 5 slivers and a m/z interval of 50–1000.

The Mass Mountaineer Mass Spectral Interpretation Tools v7.1.5.0 software (RBC Software, Peabody, MA, USA) was used for visual and multivariate statistical analysis of the metabolome profiles. This application is tailored to the use of DART-TOFMS and routine identification of unknown samples. The procedure for identification is based on the protocols presented by Price et al. (2022) but with a limited ForeST© database based on geographic distribution data from the aforementioned taxonomic databases, only including species that may occur in the DRC. We used the National Institute of Science and Technology (NIST) search algorithm to match our measurements within the ForeST© database. This results in a list of species profiles that match best with the sample measurement. Consecutively, we constructed heatmaps and Principal Component Analysis (PCA), Direct Analysis of Principal Components (DAPC) and Kernal Discriminant Analysis (KDA) classification models (threshold 10%, mass tolerance 15 mDa) for both the matching species from the NIST search and the declared species under which the timbers were sold. The heat maps enable visual interpretation to select a species for identification, and the models classify unknown samples as one of the species included in the model setup.

2.4 Identification through combining wood anatomy and chemical fingerprinting

When combining both timber identification methods, identification through microscopic analysis of wood anatomy is best used as the first analysis (Dormontt et al. 2015). It identifies a wide range of timbers up to the genus level, while potentially lacking the precision to identify up to the species level. In contrast, DART-TOFMS has a more limited scope of species due to an incomplete reference database, but results frequently in species-level identifications for genera that are well represented in the ForeST© database. The analysis of wood anatomy described earlier often produces a shortlist of species which are difficult to separate based on cell and tissue features. The combination approach then continues with an analysis in Mass Mountaineer with the metabolome profiles from species in the shortlist using the protocols described in the previous section.

3 Results

The methodology yielded microsections and a metabolome profile for each sample (Fig. 1). The data produced by the analysis of the sections and the profiles is stored in a repository (Monnoye et al. 2025). This includes the IAWA feature strings per sample, photomicrographs of the identified taxa, and heatmaps and classification models of polytypic timber genera for the DRC where specifications on the species level were possible. Table 1 shows the declarations and the resulting identifications based on the two methods and their combination for the 115 timber samples.

The performance of the methods based on the taxonomic level of the identifications is visualized in Fig. 2. The wood anatomy method identified up to genus level for 74 samples and up to species level for 41 samples (Table 1). The DART-TOFMS method led to 49 unresolved identifications ("No result" in Table 1 and Fig. 2). These are classified as "not enough reference" (26 samples) when a probable species was not sufficiently represented in ForeST© for visual and multivariate statistical analysis and "inconclusive" (19 samples) when no sufficient spectrometric variation was found between probable genera for identification. In the remaining four unresolved identifications listed as "invalidated," DART-TOFMS led to impossible species as they are unambiguously excluded by wood anatomy. Besides this, with this method 34 samples were identified up to genus and 32 up to species level. The genera *Autranella*, *Ceiba*, *Milicia*, *Ongokea*, *Petersianthus*, and *Ricinodendron* are monotypic for the DRC, accounting for 33 of the wood anatomical species level identifications and 13 of the DART-TOFMS species level identifications.

The combination approach identified up to genus level for 59 and up to species level for 56 samples respectively and thus delivered the most precise identifications. Adding DART-TOFMS after the wood anatomical analysis confirmed 46 and improved 21 of the identification results. Improvements consisted of either a new species level identification or a genus level identification where additional species of the genus could be ruled out. These occurred for the genera *Entandrophragma*, *Erythrophleum*, *Pericopsis*, and *Pterocarpus*.

As the combination of both methods had the best identification performance, we used this approach to verify the botanical species from the declarations under which the timbers were sold (Table 2). Doing so resulted in 26 falsely declared samples (23% of the collection). These misdeclarations are distributed across a variety of different timbers with three major sources. First, timbers in the Meliaceae family were frequently encountered in cases of mislabelling. This occurred both within the family (e.g., *Khaya* spp. are confused with *Entandrophragma* spp.) and with other families (e.g., one sample sold as *Uapaca guineensis* and one as *Gilbertiodendron dewevrei* are in fact both *Entandrophragma candollei*). Second, *Prioria balsamifera* was frequently interchanged with the other *Prioria* species. Third, the timbers of the genera *Alstonia* and *Ricinodendron* were often interchanged.

4 Discussion

4.1 Diagnostic features

We were able to make distinctions at the species level for several polytypic genera in the DRC. This is facilitated by the essential diagnostic features observed using the methods of this study and results in a consistent exclusion of species that occurred further away from the markets in Kisangani, for instance in provinces more to the south and west of the DRC. Hence, the small-scale markets are sourced with timber from closely surrounding forests, which is in line with existing literature (Lescuyer et al. 2014). Future identifications of timber originating from local DRC markets could thus consider using a stricter geographical delimitation of potential species, for instance by consulting the GBIF database or inventory data from surrounding forests (Dauby et al. 2016; Hubau et al. 2020).

The genus *Entandrophragma* (Meliaceae) has multiple diagnostic anatomical features that allow the distinction of the commercially important tropical DRC forest species *E. cylindricum* (Sprague) Sprague, *E. candollei* Harms, *E. angolense* (Welw) C.DC. and *E. utile* (Dawe & Sprague) Sprague. These features are described in detail

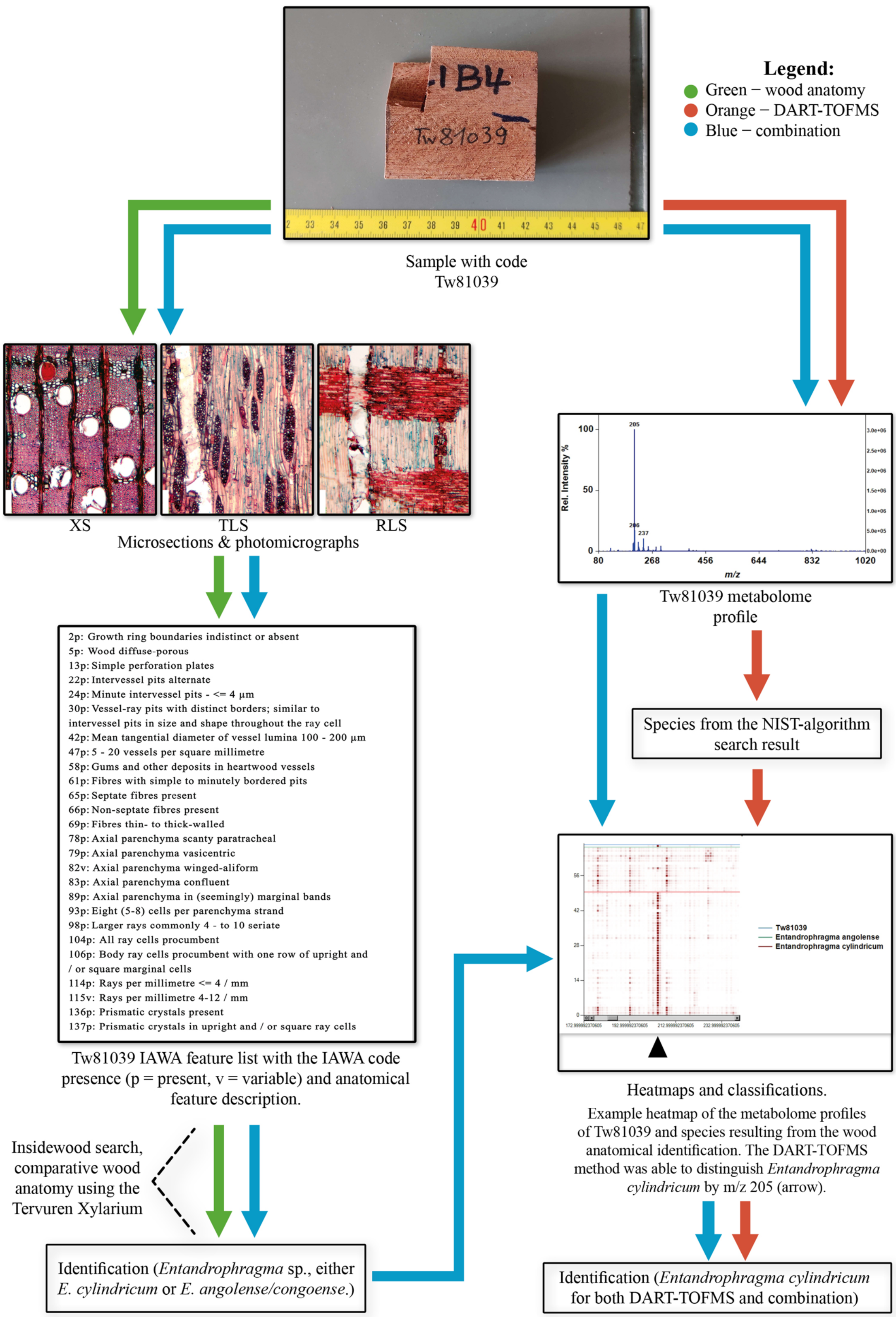

Fig. 1 Example of the gathered samples, the prepared materials and the resulting identification using the methods of this study

Table 1 Identification results of 115 tropical timber samples. Sample code, vernacular names (both international and local) and their translation to botanical species and results of the identifications with the wood anatomical, DART-TOFMS and combined approach for 115 timber samples sold on local Kisangani markets. The results are accompanied by comments when necessary for the interpretation of genus level identifications that lead to different results of the methods or misdeclarations. Identifications ending in "sp." indicate that there was no specification on the species level, barring partial specifications indicated in the comments. Vernacular names highlighted in bold are misdeclarations

Code	Vernacular name(s)	Translation	Wood anatomy	DART-TOFMS	Combination	Comments
Tw80946	Essia, Foyo	*Petersianthus macrocarpus*	*Petersianthus macrocarpus*	No result (inconclusive)	*Petersianthus macrocarpus*	The genus *Petersianthus* is monotypic in the DRC
Tw80947	Essia, Foyo	*Petersianthus macrocarpus*	*Petersianthus macrocarpus*	No result (inconclusive)	*Petersianthus macrocarpus*	The genus *Petersianthus* is monotypic in the DRC
Tw80948	Essia, Foyo	*Petersianthus macrocarpus*	*Petersianthus macrocarpus*	No result (inconclusive)	*Petersianthus macrocarpus*	The genus *Petersianthus* is monotypic in the DRC
Tw80949	Essia, Foyo	*Petersianthus macrocarpus*	*Petersianthus macrocarpus*	No result (inconclusive)	*Petersianthus macrocarpus*	The genus *Petersianthus* is monotypic in the DRC
Tw80950	Essia, Foyo	*Petersianthus macrocarpus*	*Petersianthus macrocarpus*	No result (inconclusive)	*Petersianthus macrocarpus*	The genus *Petersianthus* is monotypic in the DRC
Tw80951	Essia, Foyo	*Petersianthus macrocarpus*	*Petersianthus macrocarpus*	No result (inconclusive)	*Petersianthus macrocarpus*	The genus *Petersianthus* is monotypic in the DRC
Tw80952	Essia, Foyo	*Petersianthus macrocarpus*	*Petersianthus macrocarpus*	No result (inconclusive)	*Petersianthus macrocarpus*	The genus *Petersianthus* is monotypic in the DRC
Tw80953	Essia, Foyo	*Petersianthus macrocarpus*	*Petersianthus macrocarpus*	No result (inconclusive)	*Petersianthus macrocarpus*	The genus *Petersianthus* is monotypic in the DRC
Tw80954	Essia, Foyo	*Petersianthus macrocarpus*	*Petersianthus macrocarpus*	No result (inconclusive)	*Petersianthus macrocarpus*	The genus *Petersianthus* is monotypic in the DRC
Tw80955	Essia, Foyo	*Petersianthus macrocarpus*	*Petersianthus macrocarpus*	No result (inconclusive)	*Petersianthus macrocarpus*	The genus *Petersianthus* is monotypic in the DRC
Tw80956	Longhi rouge, Malinda	*Gambeya lacourtiana*	*Gambeya* sp.	No result (not enough reference)	*Gambeya* sp.	
Tw80957	Longhi rouge, Malinda	*Gambeya lacourtiana*	*Gambeya* sp.	No result (not enough reference)	*Gambeya* sp.	
Tw80958	Longhi rouge, Malinda	*Gambeya lacourtiana*	*Gambeya* sp.	No result (not enough reference)	*Gambeya* sp.	
Tw80959	Rikio, Mutakala, Bosenge	*Uapaca guineensis*	*Uapaca* sp.	No result (not enough reference)	*Uapaca* sp.	
Tw80960	Rikio, Mutakala, Bosenge	*Uapaca guineensis*	*Uapaca* sp.	No result (not enough reference)	*Uapaca* sp.	
Tw80961	**Rikio, Mutakala, Bosenge**	*Uapaca guineensis*	*Entandrophragma* sp.	No result (invalidated)	*Entandrophragma* sp.	Wood anatomy identification: *E. candollei* or *E. palustre*. DART-TOFMS identification: *E. utile*, which is unambiguously excluded by wood anatomy based on IAWA feature 159. Combination identification: *E. candollei* or *E. palustre*
Tw80962	Rikio, Mutakala, Bosenge	*Uapaca guineensis*	*Uapaca* sp.	No result (not enough reference)	*Uapaca* sp.	

Table 1 (continued)

Code	Vernacular name(s)	Translation	Wood anatomy	DART-TOFMS	Combination	Comments
Tw80963	**Rikio, Mutakala, Bosenge**	*Uapaca guineensis*	*Petersianthus macrocarpus*	No result (inconclusive)	*Petersianthus macrocarpus*	The genus *Petersianthus* is monotypic in the DRC
Tw80964	Rikio, Mutakala, Bosenge	*Uapaca guineensis*	*Uapaca* sp.	No result (not enough reference)	*Uapaca* sp.	
Tw80965	Rikio, Mutakala, Bosenge	*Uapaca guineensis*	*Uapaca* sp.	No result (not enough reference)	*Uapaca* sp.	
Tw80966	Limbali, Limbalu	*Gilbertiodendron dewevrei*	*Gilbertiodendron* sp.	No result (inconclusive)	*Gilbertiodendron* sp.	
Tw80967	Limbali, Limbalu	*Gilbertiodendron dewevrei*	*Gilbertiodendron* sp.	No result (inconclusive)	*Gilbertiodendron* sp.	
Tw80968	**Limbali, Limbalu**	*Gilbertiodendron dewevrei*	*Entandrophragma* sp.	No result (invalidated)	*Entandrophragma* sp.	Wood anatomy identification: *E. candollei* or *E. palustre*. DART-TOFMS identification: *E. utile*, which is unambiguously excluded by wood anatomy based on IAWA feature 159. Combination identification: *E. candollei* or *E. palustre*
Tw80969	Limbali, Limbalu	*Gilbertiodendron dewevrei*	*Gilbertiodendron* sp.	No result (inconclusive)	*Gilbertiodendron* sp.	
Tw80970	Limbali, Limbalu	*Gilbertiodendron dewevrei*	*Gilbertiodendron* sp.	No result (inconclusive)	*Gilbertiodendron* sp.	
Tw80971	**Osmalia, Sabuni**	*Fillaeopsis discophora*	*Gambeya* sp.	No result (not enough reference)	*Gambeya* sp.	
Tw80972	**Tola blanc, Tola**	*Prioria balsamifera*	*Prioria* sp.	*Prioria* sp.	*Prioria* sp.	Wood anatomy identification: P. oxyphylla or *P. gilbertii*. DART-TOFMS identification: *P. oxyphylla*, *P. gilbertii*, or *P. buchholzii*. Combination identification: *P. oxyphylla* or *P. gilbertii*
Tw80973	**Tola blanc, Tola**	*Prioria balsamifera*	*Prioria* sp.	*Prioria* sp.	*Prioria* sp.	Wood anatomy identification: *P. oxyphylla* or *P. gilbertii*. DART-TOFMS identification: *P. oxyphylla*, *P. gilbertii*,or *P. buchholzii*. Combination identification: *P. oxyphylla* or *P. gilbertii*
Tw80974	**Tola blanc, Tola**	*Prioria balsamifera*	*Prioria* sp.	*Prioria* sp.	*Prioria* sp.	Wood anatomy identification: *P. oxyphylla* or *P. gilbertii*. DART-TOFMS identification: *P. oxyphylla*, *P. gilbertii*,or *P. buchholzii*. Combination identification: *P. oxyphylla* or *P. gilbertii*
Tw80975	**Tola blanc, Tola**	*Prioria balsamifera*	*Prioria* sp.	*Prioria* sp.	*Prioria* sp.	Wood anatomy identification: *P. balsamifera* or *P. gilbertii*. DART-TOFMS identification: *P. oxyphylla*, *P. gilbertii*, or *P. buchholzii*. Combination identification: *Prioria* sp. but not *P. balsamifera* or *P. oxyphylla*

Table 1 (continued)

Code	Vernacular name(s)	Translation	Wood anatomy	DART-TOFMS	Combination	Comments
Tw80976	**Tola blanc, Tola**	*Prioria balsamifera*	*Prioria* sp.	*Prioria* sp.	*Prioria* sp.	Wood anatomy identification: *P. oxyphylla* or *P. gilbertii*. DART-TOFMS identification: *P. oxyphylla*, *P. gilbertii*,or *P. buchholzii*. Combination identification: *P. oxyphylla* or *P. gilbertii*
Tw80977	Tola blanc, Tola	*Prioria balsamifera*	*Prioria* sp.	*Prioria* sp.	*Prioria* sp.	Wood anatomy identification: *P. balsamifera* or *P. gilbertii*. DART-TOFMS identification: *P. balsamifera*, *P. gilbertii*, or *P. buchholzii*. Combination identification: *P. balsamifera* or *P. gilbertii*
Tw80978	**Tola blanc, Tola**	*Prioria balsamifera*	*Gilbertiodendron* sp.	No result (inconclusive)	*Gilbertiodendron* sp.	
Tw80979	**Tola blanc, Tola**	*Prioria balsamifera*	*Prioria* sp.	*Prioria* sp.	*Prioria* sp.	Wood anatomy identification: *P. oxyphylla* or *P. gilbertii*. DART-TOFMS identification: *P. oxyphylla*, *P. gilbertii*, or *P. buchholzii*. Combination identification: *P. oxyphylla* or *P. gilbertii*
Tw80980	**Tola blanc, Tola**	*Prioria balsamifera*	*Prioria* sp.	*Prioria* sp.	*Prioria* sp.	Wood anatomy identification: *P. oxyphylla* or *P. gilbertii*. DART-TOFMS identification: *P. oxyphylla*, *P. gilbertii*, or *P. buchholzii*. Combination identification: *P. oxyphylla* or *P. gilbertii*
Tw80981	**Tola blanc, Tola**	*Prioria balsamifera*	*Prioria* sp.	*Prioria* sp.	*Prioria* sp.	Wood anatomy identification: *P. oxyphylla* or *P. gilbertii*. DART-TOFMS identification: P. *oxyphylla*, *P. gilbertii*, or *P. buchholzii*. Combination identification: *P. oxyphylla* or *P. gilbertii*
Tw80982	Njeke	*indetermined*	*Amphimas* sp.	No result (not enough reference)	*Amphimas* sp.	
Tw80983	Essessang, Lisongo	*Ricinodendron heudelotii*	*Ricinodendron heudelotii*	No result (not enough reference)	*Ricinodendron heudelotii*	The genus *Ricinodendron* is monotypic in the DRC
Tw80984	Essessang, Lisongo	*Ricinodendron heudelotii*	*Ricinodendron heudelotii*	No result (not enough reference)	*Ricinodendron heudelotii*	The genus *Ricinodendron* is monotypic in the DRC
Tw80985	Essessang, Lisongo	*Ricinodendron heudelotii*	*Ricinodendron heudelotii*	No result (not enough reference)	*Ricinodendron heudelotii*	The genus *Ricinodendron* is monotypic in the DRC
Tw80986	**Essessang, Lisongo**	*Ricinodendron heudelotii*	*Alstonia* sp.	No result (not enough reference)	*Alstonia* sp.	
Tw80987	**Essessang, Lisongo**	*Ricinodendron heudelotii*	*Alstonia* sp.	No result (not enough reference)	*Alstonia* sp.	

Table 1 (continued)

Code	Vernacular name(s)	Translation	Wood anatomy	DART-TOFMS	Combination	Comments
Tw80988	Essessang, Lisongo	*Ricinodendron heudelotii*	*Ricinodendron heudelotii*	No result (not enough reference)	*Ricinodendron heudelotii*	The genus *Ricinodendron* is monotypic in the DRC
Tw80989	**Essessang, Lisongo**	*Ricinodendron heudelotii*	*Ceiba pentandra*	No result (not enough reference)	*Ceiba pentandra*	The genus *Ceiba* is monotypic in the DRC
Tw80990	**Emien, Mutondo**	*Alstonia boonei*	*Ricinodendron heudelotii*	No result (not enough reference)	*Ricinodendron heudelotii*	The genus *Ricinodendron* is monotypic in the DRC
Tw80991	**Emien, Mutondo**	*Alstonia boonei*	*Ricinodendron heudelotii*	No result (not enough reference)	*Ricinodendron heudelotii*	The genus *Ricinodendron* is monotypic in the DRC
Tw80992	Emien, Mutondo	*Alstonia boonei*	*Alstonia* sp.	No result (not enough reference)	*Alstonia* sp.	
Tw80993	**Kapokier, Coton**	*Bombax buonopozense*	*Ekebergia* sp.	No result (not enough reference)	*Ekebergia* sp.	
Tw80994	Bilinga, Bokese	*Nauclea diderrichii*	*Nauclea* sp.	*Nauclea* sp.	*Nauclea* sp.	
Tw80995	Bilinga, Bokese	*Nauclea diderrichii*	*Nauclea* sp.	*Nauclea* sp.	*Nauclea* sp.	
Tw80996	Bilinga, Bokese	*Nauclea diderrichii*	*Nauclea* sp.	*Nauclea* sp.	*Nauclea* sp.	
Tw80997	Mukulungu, Pilipili, Mosembe, Mayasali	*Autranella congolensis*	*Autranella congolensis*	*Autranella congolensis*	*Autranella congolensis*	The genus *Autranella* is monotypic
Tw80998	Mukulungu, Pilipili, Mosembe, Mayasali	*Autranella congolensis*	*Autranella congolensis*	*Autranella congolensis*	*Autranella congolensis*	The genus *Autranella* is monotypic
Tw80999	**Mukulungu, Pilipili, Mosembe, Mayasali**	*Autranella congolensis*	*Petersianthus macrocarpus*	No result (inconclusive)	*Petersianthus macrocarpus*	The genus *Petersianthus* is monotypic in the DRC
Tw81000	Mukulungu, Pilipili, Mosembe, Mayasali	*Autranella congolensis*	*Autranella congolensis*	*Autranella congolensis*	*Autranella congolensis*	The genus *Autranella* is monotypic
Tw81001	**Mukulungu, Pilipili, Mosembe, Mayasali**	*Autranella congolensis*	*Petersianthus macrocarpus*	No result (inconclusive)	*Petersianthus macrocarpus*	The genus *Petersianthus* is monotypic in the DRC
Tw81002	**Aielé, Kasuku, Musuku**	*Canarium schweinfurthii*	*Coelocaryon* sp.	No result (not enough reference)	*Coelocaryon* sp.	
Tw81003	Afrormosia, Mogoya	*Pericopsis elata*	*Pericopsis* sp.	*Pericopsis elata*	*Pericopsis elata*	
Tw81004	Afrormosia, Mogoya	*Pericopsis elata*	*Pericopsis* sp.	*Pericopsis elata*	*Pericopsis elata*	
Tw81005	Afrormosia, Mogoya	*Pericopsis elata*	*Pericopsis* sp.	*Pericopsis elata*	*Pericopsis elata*	
Tw81006	Afrormosia, Mogoya	*Pericopsis elata*	*Pericopsis* sp.	*Pericopsis elata*	*Pericopsis elata*	
Tw81008	Afrormosia, Mogoya	*Pericopsis elata*	*Pericopsis* sp.	*Pericopsis elata*	*Pericopsis elata*	
Tw81009	Afrormosia, Mogoya	*Pericopsis elata*	*Pericopsis* sp.	*Pericopsis elata*	*Pericopsis elata*	
Tw81010	Afrormosia, Mogoya	*Pericopsis elata*	*Pericopsis* sp.	*Pericopsis elata*	*Pericopsis elata*	
Tw81011	Afrormosia, Mogoya	*Pericopsis elata*	*Pericopsis* sp.	*Pericopsis elata*	*Pericopsis elata*	
Tw81012	Iroko	*Milicia excelsa*	*Milicia excelsa*	*Milicia excelsa*	*Milicia excelsa*	The genus *Milicia* is monotypic in the DRC
Tw81013	Iroko	*Milicia excelsa*	*Milicia excelsa*	*Milicia excelsa*	*Milicia excelsa*	The genus *Milicia* is monotypic in the DRC

Table 1 (continued)

Code	Vernacular name(s)	Translation	Wood anatomy	DART-TOFMS	Combination	Comments
Tw81014	Iroko	*Milicia excelsa*	*Milicia excelsa*	*Milicia excelsa*	*Milicia excelsa*	The genus *Milicia* is monotypic in the DRC
Tw81015	Iroko	*Milicia excelsa*	*Milicia excelsa*	*Milicia excelsa*	*Milicia excelsa*	The genus *Milicia* is monotypic in the DRC
Tw81016	Iroko	*Milicia excelsa*	*Milicia excelsa*	*Milicia excelsa*	*Milicia excelsa*	The genus *Milicia* is monotypic in the DRC
Tw81017	Iroko	*Milicia excelsa*	*Milicia excelsa*	*Milicia excelsa*	*Milicia excelsa*	The genus *Milicia* is monotypic in the DRC
Tw81018	Iroko	*Milicia excelsa*	*Milicia excelsa*	*Milicia excelsa*	*Milicia excelsa*	The genus *Milicia* is monotypic in the DRC
Tw81019	Iroko	*Milicia excelsa*	*Milicia excelsa*	*Milicia excelsa*	*Milicia excelsa*	The genus *Milicia* is monotypic in the DRC
Tw81020	Iroko	*Milicia excelsa*	*Milicia excelsa*	*Milicia excelsa*	*Milicia excelsa*	The genus *Milicia* is monotypic in the DRC
Tw81021	Padouk, Ngola	*Pterocarpus* spp.	*Pterocarpus* sp.	*Pterocarpus* sp.	*Pterocarpus* sp.	DART-TOFMS and combination identification: *P. lucens*, *P. officinalis*, *P. rotundifolius*, *P. soyauxii*, or *P. tessmannii*
Tw81022	Padouk, Ngola	*Pterocarpus* spp.	*Pterocarpus* sp.	*Pterocarpus* sp.	*Pterocarpus* sp.	DART-TOFMS and combination identification: *P. lucens*, *P. officinalis*, *P. rotundifolius*, *P. soyauxii*,or *P. tessmannii*
Tw81023	Padouk, Ngola	*Pterocarpus* spp.	*Pterocarpus* sp.	*Pterocarpus* sp.	*Pterocarpus* sp.	DART-TOFMS and combination identification: *P. lucens*, *P. officinalis*, *P. rotundifolius*, *P. soyauxii*,or *P. tessmannii*
Tw81024	Padouk, Ngola	*Pterocarpus* spp.	*Pterocarpus* sp.	*Pterocarpus* sp.	*Pterocarpus* sp.	DART-TOFMS and combination identification: *P. lucens*, *P. officinalis*, *P. rotundifolius*, *P. soyauxii*, or *P. tessmannii*
Tw81025	Padouk, Ngola	*Pterocarpus* spp.	*Pterocarpus* sp.	*Pterocarpus* sp.	*Pterocarpus* sp.	DART-TOFMS and combination identification: *P. lucens*, *P. officinalis*, *P. rotundifolius*, *P. soyauxii*, or *P. tessmannii*
Tw81026	Padouk, Ngola	*Pterocarpus* spp.	*Pterocarpus* sp.	*Pterocarpus* sp.	*Pterocarpus* sp.	DART-TOFMS and combination identification: *P. lucens*, *P. officinalis*, *P. rotundifolius*, *P. soyauxii*, or *P. tessmannii*
Tw81027	Tali	*Erythrophleum suaveolens*	*Erythrophleum* sp.	*Erythrophleum* sp.	*Erythrophleum suaveolens*	Wood anatomy identification: *E. ivorense* or *E. suaveolens.* DART-TOFMS identification: *E. suaveolens* or *E. africanum*

Table 1 (continued)

Code	Vernacular name(s)	Translation	Wood anatomy	DART-TOFMS	Combination	Comments
Tw81028	Tali	*Erythrophleum suaveolens*	*Erythrophleum* sp.	*Erythrophleum* sp.	*Erythrophleum* sp.	Wood anatomy and combination identification: *E. ivorense* or *E. suaveolens*. DART-TOFMS identification: *E. africanum*, *E. ivorense* or *E. suaveolens*
Tw81029	Tali	*Erythrophleum suaveolens*	*Erythrophleum* sp.	*Erythrophleum* sp.	*Erythrophleum suaveolens*	Wood anatomy identification: *E. ivorense* or *E. suaveolens*. DART-TOFMS identification: *E. suaveolens* or *E. africanum*
Tw81030	Tali	*Erythrophleum suaveolens*	*Erythrophleum* sp.	*Erythrophleum* sp.	*Erythrophleum suaveolens*	Wood anatomy identification: *E. ivorense* or *E. suaveolens*. DART-TOFMS identification: *E. suaveolens* or *E. africanum*
Tw81031	Acajou, Khaya	*Khaya* spp.	*Khaya* sp.	*Khaya* sp.	*Khaya* sp.	Wood anatomy, DART-TOFMS and combination identification: *K. anthotheca* or *K. grandifoliola*
Tw81032	Acajou, Khaya	*Khaya* spp.	*Khaya* sp.	*Khaya* sp.	*Khaya* sp.	Wood anatomy, DART-TOFMS and combination identification: *K. anthotheca* or *K. grandifoliola*
Tw81033	**Acajou, Khaya**	*Khaya* spp.	*Entandrophragma cylindricum*	*Entandrophragma cylindricum*	*Entandrophragma cylindricum*	
Tw81034	Acajou, Khaya	*Khaya* spp.	*Khaya* sp.	*Khaya* sp.	*Khaya* sp.	Wood anatomy, DART-TOFMS and combination identification: *K. anthotheca* or *K. grandifoliola*
Tw81035	Acajou, Khaya	*Khaya* spp.	*Khaya* sp.	*Khaya* sp.	*Khaya* sp.	Wood anatomy, DART-TOFMS and combination identification: *K. anthotheca* or *K. grandifoliola*
Tw81036	Liboyo	*Entandrophragma* spp.	*Entandrophragma* sp.	*Entandrophragma* sp.	*Entandrophragma* sp.	Wood anatomy, DART-TOFMS and combination identification: *E. candollei* or *E. palustre*
Tw81037	Liboyo	*Entandrophragma* spp.	*Entandrophragma cylindricum*	*Entandrophragma cylindricum*	*Entandrophragma cylindricum*	
Tw81038	Liboyo	*Entandrophragma* spp.	*Entandrophragma* sp.	No result (invalidated)	*Entandrophragma candollei*	Wood anatomy identification: *E. candollei* or *E. palustre*. DART-TOFMS identification: *E. utile*, which is unambiguously excluded by wood anatomy based on IAWA feature 159. Combination identification: *E. candollei*
Tw81039	Liboyo	*Entandrophragma* spp.	*Entandrophragma* sp.	*Entandrophragma cylindricum*	*Entandrophragma cylindricum*	Wood anatomy identification: *E. cylindricum*, *E. angolense*, or *E. congoense*

Table 1 (continued)

Code	Vernacular name(s)	Translation	Wood anatomy	DART-TOFMS	Combination	Comments
Tw81040	Liboyo	*Entandrophragma* spp.	*Entandrophragma* sp.	No result (inconclusive)	*Entandrophragma* sp.	Wood anatomy identification: *E. candollei* or *E. palustre*. DART-TOFMS identification: various Meliaceae genera. Combination identification: *E. candollei* or *E. palustre*
Tw81041	**Liboyo**	*Entandrophragma* spp.	*Khaya* sp.	*Khaya* sp.	*Khaya* sp.	Wood anatomy, DART-TOFMS and combination identification: *K. anthotheca* or *K. grandifoliola*
Tw81042	Liboyo	*Entandrophragma* spp.	*Entandrophragma cylindricum*	*Entandrophragma cylindricum*	*Entandrophragma cylindricum*	
Tw81043	Liboyo	*Entandrophragma* spp.	*Entandrophragma* sp.	*Entandrophragma* sp.	*Entandrophragma* sp.	Wood anatomy, DART-TOFMS and combination identification: *E. angolense* or *E. congoense*
Tw81044	Liboyo	*Entandrophragma* spp.	*Entandrophragma cylindricum*	*Entandrophragma cylindricum*	*Entandrophragma cylindricum*	
Tw81045	Liboyo	*Entandrophragma* spp.	*Entandrophragma cylindricum*	*Entandrophragma cylindricum*	*Entandrophragma cylindricum*	
Tw81046	Liboyo	*Entandrophragma* spp.	*Entandrophragma* sp.	*Entandrophragma* sp.	*Entandrophragma* sp.	Wood anatomy, DART-TOFMS and combination identification: *E. angolense* or *E. congoense*
Tw81047	Liboyo	*Entandrophragma* spp.	*Entandrophragma cylindricum*	*Entandrophragma cylindricum*	*Entandrophragma cylindricum*	
Tw81048	Liboyo	*Entandrophragma* spp.	*Entandrophragma* sp.	*Entandrophragma candollei*	*Entandrophragma candollei*	Wood anatomy identification: *E. candollei* or *E. palustre*
Tw81049	Liboyo	*Entandrophragma* spp.	*Entandrophragma* sp.	No result (invalidated)	*Entandrophragma* sp.	Wood anatomy identification: *E. candollei* or *E. palustre*. DART-TOFMS identification: *E. utile*, which is unambiguously excluded by wood anatomy based on IAWA feature 159. Combination identification: *E. candollei* or *E. palustre*
Tw81050	**Liboyo**	*Entandrophragma* spp.	*Khaya* sp.	*Khaya* sp.	*Khaya* sp.	Wood anatomy, DART-TOFMS and combination identification: *K. anthotheca* or *K. grandifoliola*
Tw81051	Alumbi	*Julbernardia seretii*	*Julbernardia* sp.	No result (not enough reference)	*Julbernardia* sp.	
Tw81052	Alumbi	*Julbernardia seretii*	*Julbernardia* sp.	No result (not enough reference)	*Julbernardia* sp.	
Tw81053	Ilomba na mokili	*Pycnanthus angolensis*	*Pycnanthus* sp.	No result (not enough reference)	*Pycnanthus* sp.	
Tw81054	Olon gille, Fagara	*Zanthoxylum gilletii*	*Zanthoxylum* sp.	*Zanthoxylum* sp.	*Zanthoxylum* sp.	
Tw81055	Latandza	*Albizia ferruginea*	*Albizia* sp.	*Albizia* sp.	*Albizia* sp.	

Table 1 (continued)

Code	Vernacular name(s)	Translation	Wood anatomy	DART-TOFMS	Combination	Comments
Tw81056	Angueuk	*Ongokea gore*	*Ongokea gore*	*Ongokea gore*	*Ongokea gore*	The genus *Ongokea* is monotypic
Tw81057	Tchitola, Tola rouge	*Prioria oxyphylla*	*Prioria* sp.	*Prioria* sp.	*Prioria* sp.	Wood anatomy identification: *P. oxyphylla* or *P. gilbertii*. DART-TOFMS identification: *P. oxyphylla*, *P. gilbertii*,or *P. buchholzii*. Combination identification: *P. oxyphylla* or *P. gilbertii*
Tw81058	Sapelli	*Entandrophragma cylindricum*	*Entandrophragma cylindricum*	*Entandrophragma cylindricum*	*Entandrophragma cylindricum*	
Tw81059	**Sipo**	*Entandrophragma utile*	*Entandrophragma cylindricum*	*Entandrophragma cylindricum*	*Entandrophragma cylindricum*	
Tw81060	Kosipo	*Entandrophragma candollei*	*Entandrophragma* sp.	*Entandrophragma candollei*	*Entandrophragma candollei*	
Tw81061	Souge	*Parinari excelsa*	*Parinari* sp.	No result (not enough reference)	*Parinari* sp.	

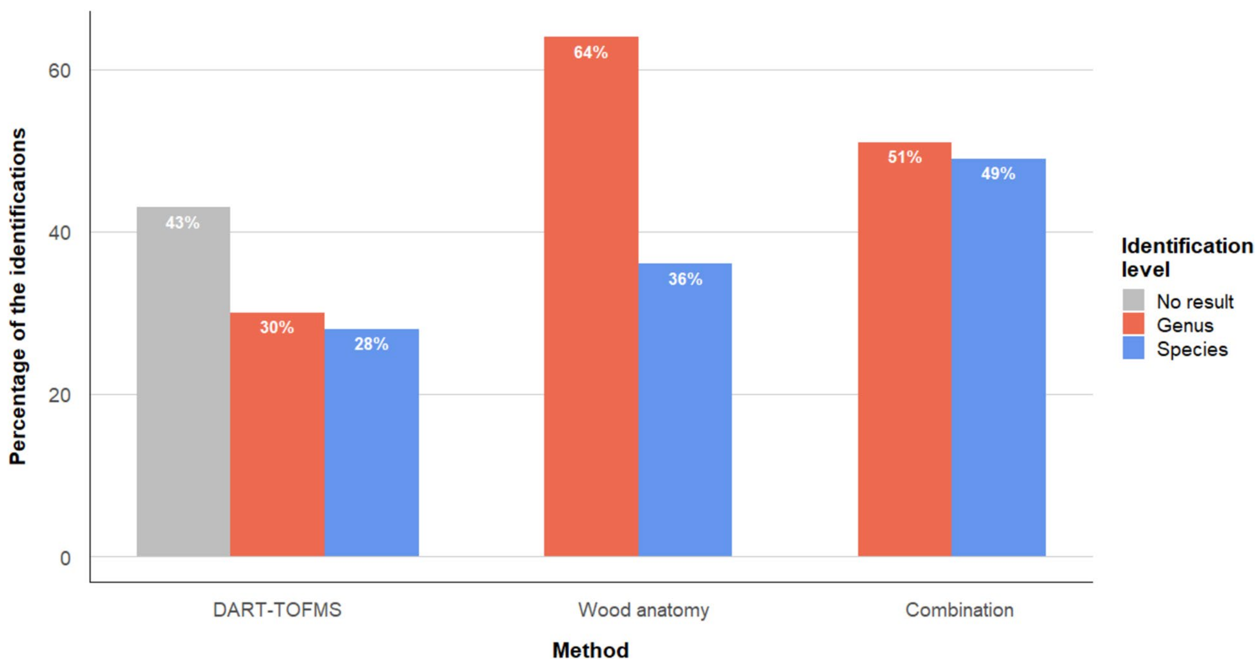

Fig. 2 Taxonomic level of the identifications of 115 timber samples sold on local Kisangani markets by wood anatomy, DART-TOFMS and a combination of both methods

by Brazier and Franklin (1961). Two additional dense forest species of minor commercial importance, *E. palustre* Staner and *E. congoense* (Pierre ex De Wild.) A.Chev. are considered for identification. We find the anatomy of the former indistinguishable from *E. candollei* and that of the latter indistinguishable from *E. angolense*. The metabolome profiles contain several diagnostic ions for *Entandrophragma* species (especially m/z 205, 483, 500, 827 and 857) (Monnoye et al. 2025), which improve the identification results when combining both techniques. However, using only DART-TOFMS results in four contradictions with the wood anatomical method. For each case, the wood is identified as *E. utile*, while the anatomy excludes this species unambiguously and instead identifies the samples as either *E. candollei* or *E. palustre*. This may be due to a lack of reference profiles (*E. candollei* only has 12) or because there are no clear diagnostic ions between these two species (Monnoye et al. 2025). We do find minor spectrometric differences between *E. palustre* and *E. candollei,* most notably for m/z 799 which has a reduced relative intensity in the reference profiles for *E. palustre*. However, *E. palustre* only has nine reference profiles, making both the visual and multivariate analysis less reliable.

Erythrophleum (Fabaceae) is represented by three species in the DRC: *E. africanum* (Welw. Ex Benth.) Harms, *E. ivorense* A. Chev. and *E. suaveolens* (Guill. & Perr.) Brenan. In contrast to *E. ivorense* and *E. suaveolens*, *E. africanum* is a savanna species that typically has smaller vessel sizes and higher vessel densities that allow it to be distinguished from the former two species despite the intraspecific variability of these features (Gorel 2019). While *E. africanum* can thus be excluded by wood anatomy, we did not find any obvious anatomical difference between *E. ivorense* and *E. suaveolens*. The metabolome profiles show at least one diagnostic ion (m/z 90) between *E. ivorense* and *E. suaveolens* facilitating the exclusion of *E. ivorense* for three samples, while no reference profiles were available for *E. africanum* (Monnoye et al. 2025). Therefore, here only the combination of both methods can identify this genus up to the species level.

In the DRC, both *Pericopsis elata* (Harms) Meeuwen and *Pericopsis angolensis* (Baker) Meeuwen (Fabaceae) can occur, of which only the former is present near Kisangani and the latter has a natural distribution in the seasonally dry biome to the south of the country. There are only lesser diagnostic anatomical features that separate the two species, but there are diagnostic spectrometric features, especially m/z 273, 285 and 287 (Deklerck et al. 2017; Monnoye et al. 2025).

The DRC contains four species of the genus *Prioria* (Fabaceae): *P. balsamifera* (Vermoesen) Breteler, *P. buchholzii* (Harms) Breteler, *P. gilbertii* (J. Léonard) Breteler and *P. oxyphylla* (Harms) Breteler. The major diagnostic anatomical feature to verify *P. balsamifera* is the smaller size of the axial canals compared to the vessels observed

Table 2 Match between the declared species and the botanical identification of 115 tropical timber samples. Vernacular names (both international and local), translation to botanical names, number of samples and number of matches between the translated botanical names and the identifications for 115 timber samples sold on local Kisangani markets

Vernacular name(s)	Translation	Samples	Match
Essia, Foyo	*Petersianthus macrocarpus*	10	10
Longhi rouge, Malinda	*Gambeya lacourtiana*	3	3
Rikio, Mutakala, Bosenge	*Uapaca guineensis*	7	5
Limbali, Limbalu	*Gilbertiodendron dewevrei*	5	4
Osmalia, Sabuni	*Fillaeopsis discophora*	1	0
Tola blanc, Tola	*Prioria balsamifera*	10	1
Njeke	indet	1	-
Essessang, Lisongo	*Ricinodendron heudelotii*	7	4
Emien, Mutondo	*Alstonia boonei*	3	1
Kapokier, Coton	*Bombax buonopozense*	1	0
Bilinga, Bokese	*Nauclea diderrichii*	3	3
Mukulungu, Pilipili, Mosembe, Mayasali	*Autranella congolensis*	5	3
Aielé, Kasuku, Musuku	*Canarium schweinfurthii*	1	0
Afrormosia, Mogoya	*Pericopsis elata*	8	8
Iroko	*Milicia excelsa*	9	9
Padouk, Ngola	*Pterocarpus* spp.	6	6
Tali	*Erythrophleum suaveolens*	4	4
Acajou, Khaya	*Khaya* spp.	5	4
Liboyo	*Entandrophragma* spp.	15	13
Alumbi	*Julbernardia seretii*	2	2
Ilomba na mokili	*Pycnanthus angolensis*	1	1
Olon gille, Fagara	*Zanthoxylum gilletii*	1	1
Latandza	*Albizia ferruginea*	1	1
Angueuk	*Ongokea gore*	1	1
Tchitola, Tola rouge	*Prioria oxyphylla*	1	1
Sapelli	*Entandrophragma cylindricum*	1	1
Sipo	*Entandrophragma utile*	1	0
Kosipo	*Entandrophragma candollei*	1	1
Souge	*Parinari excelsa*	1	1

in the transversal surface, which are instead of similar sizes in for instance *P. oxyphylla* (Monnoye et al. 2025; Rosa da Silva et al. 2017). The metabolome profiles show clear diagnostic ions distinguishing *P. balsamifera* and *P. oxyphylla* (especially m/z 301 and 305), confirming the wood anatomical exclusion of *P. balsamifera* for seven samples (Monnoye et al. 2025). As the ForeST© database does not contain reference metabolome profiles of the other two *Prioria* species, these cannot be excluded by the DART-TOFMS method.

Although the taxonomy in the genus *Pterocarpus* (Fabaceae) is not yet fully settled with reference databases such as POWO and African Plant Database showing various numbers of species, it contains at least seven species in the DRC: *P. angolensis* DC., *P. lucens* Lepr. ex Guill. & Perr., *P. officinalis* Jacq., *P. rotundifolius* (Sond.) Druce, *P. soyauxii* Taub., *P. tessmannii* Harms, and *P. tinctorius* Welw. Some of these species exhibit differences in wood anatomy (Brazier and Franklin 1961), but this is not sufficient to reach a species-level identification. There are diagnostic spectrometric features to be found in this genus (Price et al. 2021), especially m/z 163, 224, 285, and 315 for our study, allowing the DART-TOFMS approach to exclude *P. angolensis* and *P. tinctorius* during the identification process. However, a complete species-level identification of the *Pterocarpus* samples is not yet possible as *P. tessmannii* is not yet included in the ForeST© database and several other *Pterocarpus* species need additional reference profiles for the visual and multivariate analysis (Monnoye et al. 2025).

4.2 Method performance

The results show that wood anatomy is still the most precise method for the identification of central African timber. The abundance of standardized anatomical descriptions, images, literature and collections of reference microsections is a key aspect that allows this method to tackle a wide range of species (Schmitz et al. 2020). DART-TOFMS does not yet score as well for these identifications, mostly due to a lack of reference data and inconclusive results when taxa with similar metabolome profiles are encountered. Especially lesser-known timbers in genera like *Gambeya*, *Uapaca* and *Canarium* are not in the ForeST© database, which limits the number of species that can be identified. This contrasts with more internationally valued genera such as *Entandrophragma*, *Pericopsis* and *Pterocarpus*. Hence, gathering reference spectra of lesser-known species could drastically improve the performance of DART-TOFMS, emphasizing the value of sampling campaigns and reference collections such as the Tervuren Xylarium (Deklerck 2019). At the same time, even with enough reference spectra some results remain inconclusive, notably for the genera *Gilbertiodendron* and *Petersianthus* in our study. These examples show that the value of DART-TOFMS is not as a standalone method to replace the wood anatomical analysis.

The combination of both methods has the best performance for species-level identifications. These results are in line with the conclusions of existing literature on the integration of identification techniques (Dormontt et al. 2015; Low et al. 2022). In our study, this is illustrated by the new species identifications which were impossible with the individual application of wood anatomy. In other cases, partial species delimitations can be added to an identification. Although this is not the same as a species-level identification, it still forms a valuable improvement of genus-level results, for instance to verify species in the context of (inter)national forest regulations (Gasson 2011). Since the results of DART-TOFMS measurements are to an extent unrelated to wood anatomical features, confirmations from this combined approach have two sources of evidence for an identification. This greatly increases the reliability of the results.

At least three additional identification methods are currently investigated in scientific literature. Wood anatomy currently experiences rapid advances in the field of automated identification systems using computer vision. These developments have the potential to facilitate both rapid screening of timber and detailed species-level identifications (Lens et al. 2020; De Blaere et al. 2023). Genetic analysis may identify an unknown sample even down to the specimen level, meaning this technique offers great potential for precise identifications (da Silva et al. 2020; Jiao et al. 2020). However, the extraction of DNA from wood is complex compared to leaf or bud material. Especially in heartwood or after common processing techniques used in the industry, DNA is degraded, fragmented and potentially obscured by extractives and external DNA contaminations, making it tedious to retrieve (Jiao et al. 2020). Near-Infrared Spectroscopy (NIRS) has so far been proven to discern a limited number of timber species both in the lab and in the field and thus requires more research to endorse its potential compared to other methods (Low et al. 2022; Pan et al. 2022; Ramananantoandro et al. 2024; Tsuchikawa et al. 2003).

In general, the performance of all these wood identification methods to separate species depends on i) the detection of diagnostic features (for instance species-specific anatomical features or metabolites) and ii) the sufficient availability of references that allow a comparison between species to be made. As studies are performed delving into such diagnostic features and efforts are made to expand reference databases, identification methods continuously improve (Gasson et al. 2021; Yin et al. 2020). But alongside the development of individual techniques, the integration with other identification methods is a consideration that needs to be made. Wood identification is increasingly aimed at a synergistic approach between methods as the best option to maximize identification success (Dormontt et al. 2015; Gasson et al. 2021; Yin et al. 2020), a trajectory which is further validated by the results of this study.

4.3 Misdeclarations

The misdeclarations found in this study carry significant ecological and socio-economic implications. Several Meliaceae timbers listed on CITES (*Khaya*) or as Vulnerable on the International Union for Conservation of Nature (IUCN) Red List (*Khaya*, *Entandrophragma*) were involved. Combined with the rapid harvest of timbers of this family this is indicative of an even larger impact on their populations than what forest regulators are aware of (CITES (CITES 1993); Hall 2008; Ferrari and Cerutti 2023). The socio-economic impact is exemplified by the common misdeclaration of other *Prioria* species as the more sought-after *P. balsamifera* (Abeele et al. 2019). Buyers of such timbers are thus paying for a lower-valued timber, which leads to financial loss and reduced trust in the timber market. Furthermore, this creates an unfair competition, disadvantaging legitimate sellers that do offer their timber stocks under the correct name (Hirschberger et al. 2008). An important factor facilitating these practices is the highly similar appearance and wood density of these different *Prioria* timbers, which is also the case between varying Meliaceae timbers (White and Gasson 2008) and between *Ricinodendron heudelotii* and *Alstonia* spp.

Botanical identifications are thus imperative for a better understanding of timber flows in the DRC and the resulting pressures exerted on its tropical forests. Moreover, they are essential for the implementation of national and international forest laws. While parts of the world already make strides in legislation and enforcement at the end of the supply chain of tropical timber, both existing literature and this study show that it is also necessary at the start (Barber and Canby 2018); Polo Villanueva et al. 2023). This requires the installation and expansion of forensic wood centres that can provide botanical identification services and related research, without which forest law cannot be properly enforced by either timber producing or importing countries.

5 Conclusion

Wood anatomy performs better than DART-TOFMS for the identification of tropical timber from small-scale markets in the DRC. This is mostly caused by a lack of reference metabolome profiles of internationally lesser-known timbers and a lack of diagnostic spectrometric features for some taxa. However, using DART-TOFMS to finetune the results from wood anatomy results in the best performance for species identifications, demonstrating the importance of a synergistic approach to timber identification. The identifications reveal the presence of mislabelled timber sold on these markets, which has repercussions on species conservation in the surrounding forests and socio-economic welfare in the region and underlines the need for identification services throughout the timber supply chain.

Acknowledgements
We would like to express our gratitude to the Royal Museum for Central Africa, Yangambi Wood Biology Laboratory and INERA-Yangambi for their aid in this study. This research was funded by the Belgian Science Policy Office (Belspo) (RT/22/ENFORCE) and the Development Cooperation Instrument (DCI) No. 41928 of the European Union (Action DCI-ENV 2020/416-397).

Authors' contributions
Conceptualization, T.D.M., N.B., N.L. and H.B.; formal analysis, M.M.; investigation, M.W., M.M. and K.L.; writing - original draft preparation, M.M.; writing - review and editing, H.B, W.H., M.D.R, R.D.B., J.V.d.B. and V.D.K.; visualization, M.M.; supervision, H.B., T.D.M and W.H.; project administration, F.L., H.B., T.D.M. and N.L.; funding acquisition, T.D.M, H.B. and W.H.

Data availability
Data is provided within the manuscript or supplementary information files. Supplementary material is provided in a public repository and can be accessed via the following: https://doi.org/10.6084/m9.figshare.c.7957109.v3 The repository contains a collection of the IAWA feature strings per sample, heatmaps and classifications of the metabolome profiles via DART-TOFMS and photomicrographs of the identified taxa.

Declarations

Competing interests
The authors declare no competing interests.

Author details
[1]Royal Museum for Central Africa, Tervuren, Belgium. [2]UGent-Woodlab, Department of Environment, Faculty of Bioscience Engineering, Ghent University, Gent, Belgium. [3]University of Liège, Gembloux Agro-Bio Tech, Terra-Forest is life, Liége, Belgium. [4]Ecole Régionale Post Universitaire d'Aménagement et de Gestion Intégrés des Forêts et Territoires Tropicaux, Kinshasa, Democratic Republic of the Congo. [5]Faculty of Agricultural Sciences and Environment, Department of Renewable Natural Resources Management, Université Catholique du Graben, Butembo, Democratic Republic of the Congo. [6]Meise Botanic Garden, Meise, Belgium. [7]Faculty of Renewable Natural Resources Management, University of Kisangani, Kisangani, Democratic Republic of the Congo.

Received: 23 May 2025 Accepted: 4 November 2025
Published online: 24 November 2025

References

Abeele SV, Hardy OJ, Beeckman H, Ilondea BA, Janssens SB (2019) Genetic markers for species conservation and timber tracking: development of microsatellite primers for the tropical African tree species *Prioria balsamifera* and *Prioria oxyphylla*. Forests 10:1037. https://doi.org/10.3390/f10111037

African Plant Database: Conservatoire et Jardin botaniques de la Ville de Genève and South African National Biodiversity Institute Pretoria (2025) African Plant Database (version 4.0.0). http://africanplantdatabase.ch. Accessed 23 May 2025.

Baas P, Blokhina N, Fujii T, Gasson PE, Grosser D, Heinz I, Ilic J, Xiaomei J, Miller R, Newsom L, Noshiro S, Richter HG, Suzuki M, Terrazas T, Wheeler E, Wiedenhoeft A (2004) IAWA list of microscopic features for softwood identification. IAWA J 25:1–70. https://doi.org/10.1163/22941932-90000349

Barber CV, Canby K (2018) Assessing the timber legality strategy in tackling deforestation. World Resources Institute. [Working Paper]. https://wri-indonesia.org/sites/default/files/ending-tropical-deforestation-assessing-timber-legality-strategy_0.pdf. Accessed 23 May 2025

Beeckman H (2003) A xylarium for the sustainable management of biodiversity: the wood collection of the Royal Museum for Central Africa, Tervuren, Belgium. Bulletin de l'APAD 26. https://doi.org/10.4000/apad.3613

Brazier JD, Franklin GL (1961) Identification of Hardwoods: A Microscope Key. H.M. Stationery Office, London

Brearley FQ, Adinugroho WC, Cámara-Leret R, Krisnawati H, Ledo A, Qie L, Smith TEL, Aini F, Garnier F, Lestari NS, Mansur M, Murdjoko A, Oktarita S, Soraya E, Tata HL, Tiryana T, Trethowan LA, Wheeler CE, Abdullah M, Aswandi BBJW, Cantarello E, Dunggio I, Gunawan H, Heatubun CD, Arini DID, TE Istomo K, Kuswandi R, Mutaqien Z, Pangala SR, Ramadhanil P, Puspanti A, Qirom MA, Rozak AH, Sadili A, Samsoedin I, Sulistyawati E, Sundari S, Sutomo TAP, Webb CO (2019) Opportunities and challenges for an Indonesian forest monitoring network. Ann for Sci 76:54. https://doi.org/10.1007/s13595-019-0840-0

CITES (1993) Proposal for Inclusion of *Entandrophragma* spp. in Appendix II. https://cites.org/sites/default/files/eng/cop/09/prop/E09-Prop-99_Entandrophragma.PDF. Accessed 23 May 2025.

Cody RB, Laramée JA, Durst HD (2005) Versatile new ion source for the analysis of materials in open air under ambient conditions. Anal Chem 77:2297–2302. https://doi.org/10.1021/ac050162j

da Silva JL, Bordalo R, Pissarra J (2020) Wood identification: an overview of current and past methods. Estudos de Conservação e Restauro 12: 45–68. https://doi.org/10.34632/ecr.2020.10680

Dauby G, Zaiss R, Blach-Overgaard A, Catarino L, Damen T, Deblauwe V, Dessein S, Dransfield J, Droissart V, Duarte MC, Engledow H, Fadeur G, Figueira R, Gereau RE, Hardy OJ, Harris DJ, de Heij J, Janssens S, Klomberg Y, Ley AC, Mackinder BA, Meerts P, van de Poel JL, Sonké B, Sosef MSM, Stévart T, Stoffelen P, Svenning J-C, Sepulchre P, van der Burgt X, Wieringa JJ, Couvreur TLP (2016) RAINBIO: a mega-database of tropical African vascular plants distributions. PhytoKeys 74:1–18. https://doi.org/10.3897/phytokeys.74.9723

De Blaere R, Lievens K, Van Hassel D, Deklerck V, De Mil T, Hubau W, Van Acker J, Bourland N, Verwaeren J, Van den Bulcke J, Beeckman H (2023) SmartWoodID - an image collection of large end-grain surfaces to support wood identification systems. Database 2023. https://doi.org/10.1093/database/baad034

Deklerck V (2019) National treasure: valorisation of the Federal Xylarium of Belgium for timber identification and wood technology. Dissertation, Ghent University. http://hdl.handle.net/1854/LU-8635546

Deklerck V, Finch K, Gasson PE, Van den Bulcke J, Van Acker J, Beeckman H, Espinoza E (2017) Comparison of species classification models of mass spectrometry data: Kernel Discriminant Analysis vs Random Forest; A case study of Afrormosia (*Pericopsiselata* (Harms) Meeuwen). Rapid Commun Mass Spectrom 31:1582–1588. https://doi.org/10.1002/rcm.7939

Deklerck V, Mortier T, Goeders N, Cody RB, Waegeman W, Espinoza E, Van Acker J, Van den Bulcke J, Beeckman H (2019) A protocol for automated timber species identification using metabolome profiling. Wood Sci Technol 53:953–965. https://doi.org/10.1007/s00226-019-01111-1

DIAF (2017) Liste des essences forestières de la République Démocratique du Congo. https://medd.gouv.cd/wp-content/uploads/2019/08/GO-02%20Liste%20des%20essences%20forestières%20de%20RDC.pdf. Accessed 23 May 2025.

Dormontt EE, Boner M, Braun B, Breulmann G, Degen B, Espinoza E, Gardner S, Guillery P, Hermanson JC, Koch G, Lee SL, Kanashiro M, Rimbawanto A, Thomas D, Wiedenhoeft AC, Yin Y, Zahnen J, Lowe AJ (2015) Forensic timber identification: it's time to integrate disciplines to combat illegal logging. Biol Conserv 191:790–798. https://doi.org/10.1016/j.biocon.2015.06.038

Espinoza EO, Wiemann MC, Barajas-Morales J, Chavarria GD, McClure PJ (2015) Forensic analysis of CITES-protected *Dalbergia* timber from the Americas. IAWA J 36:311–325. https://doi.org/10.1163/22941932-20150102

Evans PD, Mundo IA, Wiemann MC, Chavarria GD, McClure PJ, Voin D, Espinoza EO (2017) Identification of selected CITES-protected Araucariaceae using DART TOFMS. IAWA J 38:266–281. https://doi.org/10.1163/22941932-20170171

Ferrari S, Cerutti PO (2023) Timber trade in the eastern Democratic Republic of the Congo (DRC): effectiveness of timber parks in tackling tax frauds. Int Forestry Rev 25:177–189. https://doi.org/10.1505/146554823837244446
Gärtner H, Schweingruber F (2013) Microscopic preparation techniques for plant stem analysis. Kessel Publishing House, Remagen
Gasson PE (2011) How precise can wood identification be? Wood anatomy's role in support of the legal timber trade, especially CITES. IAWA J 32:137–154. https://doi.org/10.1163/22941932-90000049
Gasson PE, Lancaster CA, Young R, Redstone S, Miles-Bunch IA, Rees G, Guillery RP, Parker-Forney M, Lebow ET (2021) WorldForestID: addressing the need for standardized wood reference collections to support authentication analysis technologies; a way forward for checking the origin and identity of traded timber. Plants People Planet 3(2):130–141. https://doi.org/10.1002/ppp3.10164
GBIF.org (2025) The Global Biodiversity Information Facility. https://www.gbif.org. Accessed 23 May 2025.
Gerland P, Raftery AE, Ševčíková H, Li N, Gu D, Spoorenberg T, Alkema L, Fosdick BK, Chunn J, Lalic N, Bay G, Buettner T, Heilig GK, Wilmoth J (2014) World population stabilization unlikely this century. Science 346:234–237. https://doi.org/10.1126/science.1257469
Gorel AP (2019) Climatic niche evolution within tropical tree lineages: the case of the *Erythrophleum* genus (Fabaceae – Caesalpinioideae) in Africa. Dissertation, Université de Liège. https://hdl.handle.net/2268/239692
Hall JS (2008) Seed and seedling survival of African mahogany (*Entandrophragma* spp.) in the Central African Republic: implications for forest management. For Ecol Manage 255:292–299. https://doi.org/10.1016/j.foreco.2007.09.050
He T, Marco J, Soares R, Yin Y, Wiedenhoeft AC (2020) Machine Learning Models with Quantitative Wood Anatomy Data Can Discriminate between *Swietenia macrophylla* and *Swietenia mahagoni*. Forests 11:36. https://doi.org/10.3390/f11010036
Hirschberger P, Griesshammer N, Schulmeister A (2008) Illegal wood for the European market. WWF-Germany. https://assets.wwf.org.uk/downloads/european_market_wood.pdf. Accessed 23 May 2025.
Hubau W, Van den Bulcke J, Kitin P, Mees F, Van Acker J, Beeckman H (2012) Charcoal identification in species-rich biomes: A protocol for Central Africa optimised for the Mayumbe forest. Rev Palaeobot Palynol 171:164–178. https://doi.org/10.1016/j.revpalbo.2011.11.002
Hubau W, Lewis SL, Phillips OL, Affum-Baffoe K, Beeckman H, Cuní-Sanchez A, Daniels AK, Ewango CEN, Fauset S, Mukinzi JM, Sheil D, Sonké B, Sullivan MJP, Sunderland TCH, Taedoumg H, Thomas SC, White LJT, Abernethy KA, Adu-Bredu S, Amani CA, Baker TR, Banin LF, Baya F, Begne SK, Bennett AC, Benedet F, Bitariho R, Bocko YE, Boeckx P, Boundja P, Brienen RJW, Brncic T, Chezeaux E, Chuyong GB, Clark CJ, Collins M, Comiskey JA, Coomes DA, Dargie GC, de Haulleville T, DjuikouoKamdem MN, Doucet JL, Esquivel-Muelbert A, Feldpausch TR, Fofanah A, Foli EG, Gilpin M, Gloor E, Gonmadje C, Gourlet-Fleury S, Hall JS, Hamilton AC, Harris DJ, Hart TB, Hockemba MBN, Hladik A, Ifo SA, Jeffery KJ, Jucker T, KasongoYakusu E, Kearsley E, Kenfack D, Koch A, Leal ME, Levesley A, Lindsell JA, Lisingo J, Lopez-Gonzalez G, Lovett JC, Makana JR, Malhi Y, Marshall AR, Martin J, Martin EH, Mbayu FM, Medjibe VP, Mihindou V, Mitchard ETA, Moore S, Munishi PKT, NssiBengone N, Ojo L, Ondo FE, Peh KSH, Pickavance GC, Poulsen AD, Poulsen JR, Qie L, Reitsma J, Rovero F, Swaine MD, Talbot J, Taplin J, Taylor DM, Thomas DW, Toirambe B, Tshibamba Mukendi J, Tuagben D, Umunay PM, van der Heijden GMF, Verbeeck H, Vleminckx J, Willcock S, Wöll H, Woods JT, Zemagho L (2020) Asynchronous carbon sink saturation in African and Amazonian tropical forests. Nature 579:80–87. https://doi.org/10.1038/s41586-020-2035-0
Jiao L, Lu Y, He T, Guo J, Yin Y (2020) DNA barcoding for wood identification: global review of the last decade and future perspective. IAWA J 41:620–643. https://doi.org/10.1163/22941932-bja10041
Kitin P, Espinoza E, Beeckman H, Abe H, McClure PJ (2021) Direct analysis in real-time (DART) time-of-flight mass spectrometry (TOFMS) of wood reveals distinct chemical signatures of two species of *Afzelia*. Ann For Sci 78:31. https://doi.org/10.1007/s13595-020-01024-1
Lawson S (2014) Illegal Logging in the Democratic Republic of the Congo. Chatham House. https://www.chathamhouse.org/sites/default/files/home/chatham/public_html/sites/default/files/20140400LoggingDRCLawson.pdf. Accessed 23 May 2025.
Lejoly J, Ndjele M-B, Geerinck D (2010) Catalogue-Flore des plantes vasculaires des districts de Kisangani et de la Tshopo (RD Congo). Taxonomania 30.
Lens F, Liang C, Guo Y, Tang X, Jahanbanifard M, Soares Correa Da Silva F, Ceccantini G, Verbeek FJ (2020) Computer-assisted timber identification based on features extracted from microscopic wood sections. IAWA J 41:660–680. https://doi.org/10.1163/22941932-bja10029
Lescuyer G, Cerutti PO, Tshimpanga P, Biloko F, Adebu-Abdala B, Tsanga R, Yembe-Yembe RI, Essiane-Mendoula E (2014) The domestic market for small-scale chainsaw milling in the Democratic Republic of Congo: Present situation, opportunities and challenges. CIFOR. https://doi.org/10.17528/cifor/005040
Low MC, Schmitz N, Boeschoten LE, Cabezas JA, Cramm M, Haag V, Koch G, Meyer-Sand BRV, Paredes-Villanueva K, Price E, Thornhill AH, Van Brusselen J, Zuidema PA, Deklerck V, Dormontt EE, Shapcott A, Lowe AJ (2022) Tracing the world's timber: the status of scientific verification technologies for species and origin identification. IAWA J 44:63–84. https://doi.org/10.1163/22941932-bja10097
Monnoye M, Wasukundi SM, Bourland N, De Blaere R, Deklerck V, De Mil T, De Ridder M, Hubau W, Laurent F, Liévens K, Luambua NK, Van den Bulcke J, Beeckman H (2025) Combining wood anatomy and chemical fingerprinting maximizes tropical timber identification success: supplementary information. Figshare Repository. https://doi.org/10.6084/m9.figshare.c.7957109.v3
Miller RB, Cahow E (1989) Wood identification of commercially important North American species of birch (*Betula*). IAWA J 10:364–373. https://doi.org/10.1163/22941932-90001125
Pan X, Qiu J, Yang Z (2022) Identification of Five Similar Cinnamomum Wood Species Using Portable Near-Infrared Spectroscopy. Spectroscopy 37: 16–23,49. https://doi.org/10.56530/spectroscopy.zg7089n4
Peel MC, Finlayson BL, McMahon TA (2007) Updated world map of the Köppen-Geiger climate classification. Hydrol Earth Syst Sci 11:1633–1644. https://doi.org/10.5194/hess-11-1633-2007
Polo Villanueva FD, Tegegne YT, Winkel G, Cerutti PO, Ramcilovic-Suominen S, McDermott CL, Zeitlin J, Sotirov M, Cashore B, Wardell DA, Haywood A, Giessen L (2023) Effects of EU illegal logging policy on timber-supplying countries: a systematic review. J Environ Manage 327:116874. https://doi.org/10.1016/j.jenvman.2022.116874
POWO (2025) Plants of the World Online. Facilitated by the Royal Botanic Gardens, Kew. https://powo.science.kew.org/. Accessed 23 May 2025
Price ER, Miles-Bunch IA, Gasson PE, Lancaster CA (2021) *Pterocarpus* wood identification by independent and complementary analysis of DART-TOFMS, microscopic anatomy, and fluorescence spectrometry. IAWA J 42:397–418. https://doi.org/10.1163/22941932-bja10064
Price ER, McClure PJ, Huffman AN, Voin D, Espinoza EO (2022) Reliability of wood identification using DART-TOFMS and the ForeST© database: a validation study. Forensic Sci Int Animals Environ 2:100045. https://doi.org/10.1016/j.fsiae.2022.100045
Ramananantoandro T, Rasoamanana LP, Randriambinintsoa T, Raobelina AC, Razafindramanitra Z, Chaix G (2024) A low-cost and portable near infrared spectrometer connected to a smartphone for identifying Dalbergia, Diospyros and substitute species in Madagascar. IUFRO 2024 World Congress: Forests and Society Towards 2050. Swedish University of Agricultural Sciences, June 2024, Stockholm, Sweden. Book of abstracts: 3518. https://iufro2024.com/book-of-abstracts/
Rosa Da Silva N, De Ridder M, Baetens JM, Van den Bulcke J, Rousseau M, Martinez Bruno O, Beeckman H, Van Acker J, De Baets B (2017) Automated classification of wood transverse cross-section micro-imagery from 77 commercial Central-African timber species. Ann for Sci 74:30. https://doi.org/10.1007/s13595-017-0619-0
Schmitz N (2010) Lab protocol for basic wood anatomy procedures: making and staining of micro-sections of wood samples. Royal Museum for Central Africa.
Schmitz N, Beeckman H, Jolivet-Blanc C, Boeschoten L, Braga JWB, Cabezas JA, Chaix G, Crameri S, Degen B, Deklerck V, Dormontt E, Espinoza E, Gasson PE, Haag V, Helmling S, Horacek M, Koch G, Lancaster CA, Lens F, Lowe A, Martinez-Jarquin S, Nowakowska JA, Olbrich A, Paredes-Villanueva K, Pastore TCM, Ramananantoandro T, Razafimahatratra AR, Ravindran P, Rees G, Soares LF, Tysklind N, Vlam M, Watkinson C, Wheeler E, Winkler R, Wiedenhoeft AC, Zemke VTh, Zuidema P (2020) Overview of current practices in data analysis for wood identification: a guide for the different timber tracking methods. GTTN, Global Timber Tracking Network: GTTN Secretariat: European Forest Institute and Thunen Institute

Stäuble T, Nogueron R, Knorr-Evans M, Schneider T (2023) Timber Traceability: A Diagnostic Tool for Practitioners and Policymakers. World Resources Institute. https://doi.org/10.46830/wrirpt.21.00067
Tailfer Y (1989) La forêt dense d'Afrique Centrale. Identification pratique des principaux arbres. Tome I. Approche forestière et morpho-logique (CTA). Agence de coopération culturelle et technique, Paris
Tsuchikawa S, Inoue K, Noma J, Hayashi K (2003) Application of near-infrared spectroscopy to wood discrimination. J Wood Sci 49(1):29–35. https://doi.org/10.1007/s100860300005
Tyukavina A, Hansen MC, Potapov P, Parker D, Okpa C, Stehman SV, Kommareddy I, Turubanova S (2018) Congo Basin forest loss dominated by increasing smallholder clearing. Sci Adv 4(11). https://doi.org/10.1126/sciadv.aat2993
WFO (2025) World Flora Online. http://www.worldfloraonline.org/. Accessed 23 May 2025
Wheeler EA (2011) Inside Wood – A Web resource for hardwood anatomy. IAWA J 32(2):199–211. http://dx.doi.org/10.1163/22941932-90000051
Wheeler EA, Baas P (1998) Wood Identification - A Review. IAWA J 19(3):241–264. https://doi.org/10.1163/22941932-90001528
Wheeler EA, Baas P, Gasson PE (1989) IAWA List of Microscopic Features for Hardwood Identification by an IAWA Committee. IAWA Bulletin 10(3):219–332.
White L, Gasson PE (2008) Mahogany. Kew Publishing, Royal Botanic Gardens, Kew
Wilkie P, Saridan A (1999) The limitations of vernacular names in an inventory study, Central Kalimantan, Indonesia. Biodiversity & Conservation 8:1457–1467. https://doi.org/10.1023/A:1008930012467
Yin Y, Wiedenhoeft AC, Donaldson L (2020) Advancing Wood Identification – Anatomical and Molecular Techniques. IAWA J 41(4):391–392. https://doi.org/10.1163/22941932-00002150