USE OF A PORTABLE NEAR INFRARED SPECTROMETER FOR WOOD IDENTIFICATION OF FOUR *DALBERGIA* SPECIES FROM MADAGASCAR

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Abstract.   This study focused on the use of Near InfraRed (NIR) Spectroscopy to address the lack of tools and skills for wood identification of *Dalbergia* species from Madagascar. Two sample sets of 41 wood blocks and 41 wood cores belonging to four *Dalbergia* species (*D. abrahamii*, *D. chlorocarpa*, *D. greveana*, and *D. pervillei*) were collected in the northern and western regions of Madagascar. Sapwood and heartwood NIR spectra were measured on wood at 12% moisture content by using a portable VIAVI MicroNIR 1700 spectrometer. Four discrimination models corresponding to sapwood and heartwood of the two sample forms were developed using Partial Least Square Discriminant Analysis (PLSDA).

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Good accuracy of 83.3% and 81.8% were obtained from the heartwood-based PLSDA models respectively for wood blocks and wood cores samples. All *D. chlorocarpa* samples were well-classified by the two models. Results highlighted the potential of portable NIR Spectroscopy as a helpful tool to support sustainable management and trade of Madagascar's *Dalbergia* species. Further studies are, however, needed for its operational use in identification routine.

Keywords: Discrimination, Near InfraRed Spectroscopy, portable spectrometer, PLSDA, *Dalbergia*, Madagascar.

INTRODUCTION

Dalbergia is a botanical genus comprising about 250 tree species, shrubs, and lianas (Yin et al 2018), widespread in tropical and subtropical regions (Saha et al 2013). Several *Dalbergia* tree species known under the trade names of rosewood and palisander provide valuable wood, which is harvested for making musical instruments (Wegst 2006; Perez and Marconi 2018) and furniture (Kaner et al 2013). Despite the Convention on International Trade of Endangered Species (CITES) restrictions, Madagascar's precious wood resources are illegally logged and traded to supply the illegal wood market (Patel 2007; Schuurman and Lowry 2009; Randriamalala and Liu 2010; Ratsimbazafy et al 2016; Weaber et al 2019).

There are 84 identified *Dalbergia* species from Madagascar, 83 of which are endemics. A total of 58 species can provide large trees with a diameter larger than 20 cm and serve as sources of precious wood (Phillipson et al 2022). There was an increase in their illegal logging after the 2009 due to political instability and the increase in demand for precious wood on the international market (Ratsimbazafy et al 2016). Nearly 40,000 tons of rosewood from Madagascar were exported illegally from 2008 to 2010, 64% of which were exported in 2009 only (Ratsimbazafy et al 2016). To enable a sustainable management and trade of these resources, all Madagascar's *Dalbergia* species were listed in the Appendix II of the CITES in 2013 under the Malagasy Government recommendation (Ratsimbazafy et al 2016).

The CITES implementation allowing to regulate international trade of wood species requires a good taxonomic knowledge based on wood anatomy to identify felled timbers (CITES 2019). However, in Madagascar as throughout the world,

very few experts possess these skills. Several alternative methods are currently being tested and/or used to identify tree species or their geographical origin from wood specimens (Schmitz et al 2020). These include the use of mass spectrometry (Espinoza et al 2015; Mcclure et al 2015; Evans et al 2017; Zhang et al 2019; Brunswick et al 2021), analyses of stable isotope ratios of chemical elements (C, O, H, S, N, and Sr), characterizing the environmental conditions of the tree's growing site (Micha et al 2009; Rees 2015; Hajj et al 2017), genetic analysis based on molecular markers on wood DNA (Hassold et al 2016; Fatima et al 2019), Laser Induced Breakdown Spectroscopy (Celani et al 2019), and Near InfraRed (NIR) Spectrometry (Pastore et al 2011; Snel et al 2018). Among those existing techniques, wood anatomy, DNA barcoding, and NIR Spectroscopy were already tested and currently under development by Malagasy scientists for the identification of Madagascar's *Dalbergia* species.

NIR Spectroscopy with chemometrics, as an approach based on the signal processing, is described in the literature (Tsuchikawa and Kobori 2015). Pastore et al (2011) used NIR Spectroscopy to separate four anatomically similar wood species (*Swietenia macrophylla* King, *Carapa guanensis* Aubl, *Cedrela odorata* L. and *Micropholis melinoniana* Pierre) from wood powder by using Partial Least Square Discriminant Analysis (PLSDA). One published study only has been done so far in the literature regarding the discrimination of wood species belonging to the same *Dalbergia* genus using NIR Spectroscopy (Snel et al 2018). Snel et al (2018) used NIR Spectroscopy with PLSDA to discriminate six CITES-listed *Dalbergia* species from America and Asia (*D. decipularis* Rizzini and A. Mattos, *D. sisso* DC, *D. stevensonii* Standl, *D. latifolia* Roxb, *D. retusa* Hemsl, and *D. nigra*

[Vell.] Benth) from heartwood spectra by using a portable NIR Spectrometer. NIR Spectroscopy have not yet been carried out for *Dalbergia* from Madagascar. In light of the illegal trafficking of Madagascar's precious wood and their inclusion in CITES Appendix II, the development of a rapid and inexpensive tool to assist in the identification of these species is of crucial interest. Laboratory spectrometers are more efficient and stable than portable instruments, but their acquisition cost is relatively expensive (up to 70 times). Miniaturization of NIR Spectrometer instrumentation has improved its deployability resulting in its increased use both for laboratory and in-field measurements even with limited spectral resolution and range (Yan and Siesler 2018; Zhu et al 2021; Giussani et al 2022).

Species discrimination from wood material using NIR Spectroscopy is usually carried out on wood blocks (Pastore et al 2011; Snel et al 2018) or wood powder (Bergo et al 2016). Using wood cores is not very common despite it is a less invasive method of wood sampling (Van Mantgem and Stephenson 2004; Helcoski et al 2019). Wood cores also allow consideration of the variability of wood chemical properties radially through the wood. This work addresses method development for the classification of four *Dalbergia* species of Madagascar using a handheld VIAVI MicroNIR 1700 spectrometer and investigates the impact of sample form (block *vs.* core) and wood type (heartwood *vs.* sapwood).

MATERIALS AND METHODS

Wood Blocks and Wood Cores Sampling

Sampling sites were located inside and outside of protected forest areas in Boeny, Diana, Sofia, Betsiboka, and Menabe regions of Madagascar (Fig 1). It was not possible to sample each of the four species in the five regions due to geographic distributions. A total of 41 wood cores belonging to *D. chlorocarpa* R. Vig., *D. greveana* Baill., and *D. abrahamii* Bosser & R. Rabev. and 41 wood blocks belonging to *D. chlorocarpa*, *D. greveana*, and *D. pervillei* Vatke (Fig 2[a], Table 1) were collected between 2016 and 2019

from a total of 67 trees. Wood blocks and cores were collected from trees with a diameter larger than 20 cm. Wood cores with a diameter of 5 mm were collected at 1.30 m from the ground, from pith to bark and in a perpendicular direction to the tree axis using a Pressler borer. Wood blocks (4 cm×4 cm×4 cm) were sampled from the tree trunk just below 1.30 m from the ground. An herbarium voucher was also prepared for each tree for botanical verification. Species identification was carried out by taxonomists from Missouri Botanical Garden Madagascar and National Museum of Natural History France.

Wood Moisture Conditioning

To minimize moisture effects due to moisture variation, all samples were stabilized at 12% theoretical moisture content in a climatic chamber at 20°C and 65% relative humidity. The wood moisture content of 12% was reached when the difference in mass between two measurements spaced in 24-h intervals for four reference samples did not exceed ±5%.

NIR Measurements

NIR absorbance spectra were measured on moisture stabilized wood samples with a portable MicroNIR VIAVI 1700 spectrometer (Viavi Solution–Milpitas, CA). Heartwood and sapwood NIR spectra measurements (Fig 2[b]) were made in diffuse reflection mode from 900 to 1700 nm. Each measurement was an average of 100 scans and the integration time was set to 10 ms. A Spectralon (99% reflectance) was used as reference background. NIR measurements were made on the transversal face for wood blocks, whereas they were made on unidentified face for wood cores since it was difficult to detect the wood ligneous plane.

Three spectra were collected radially from pith to bark for the sapwood and heartwood of each sample ($n = 420$) and then averaged ($n = 140$). These averaged spectra were divided in four spectral datasets (Table 2) according to sample form (block or core) and wood type (sapwood or heartwood). Each dataset consists of a spectral data
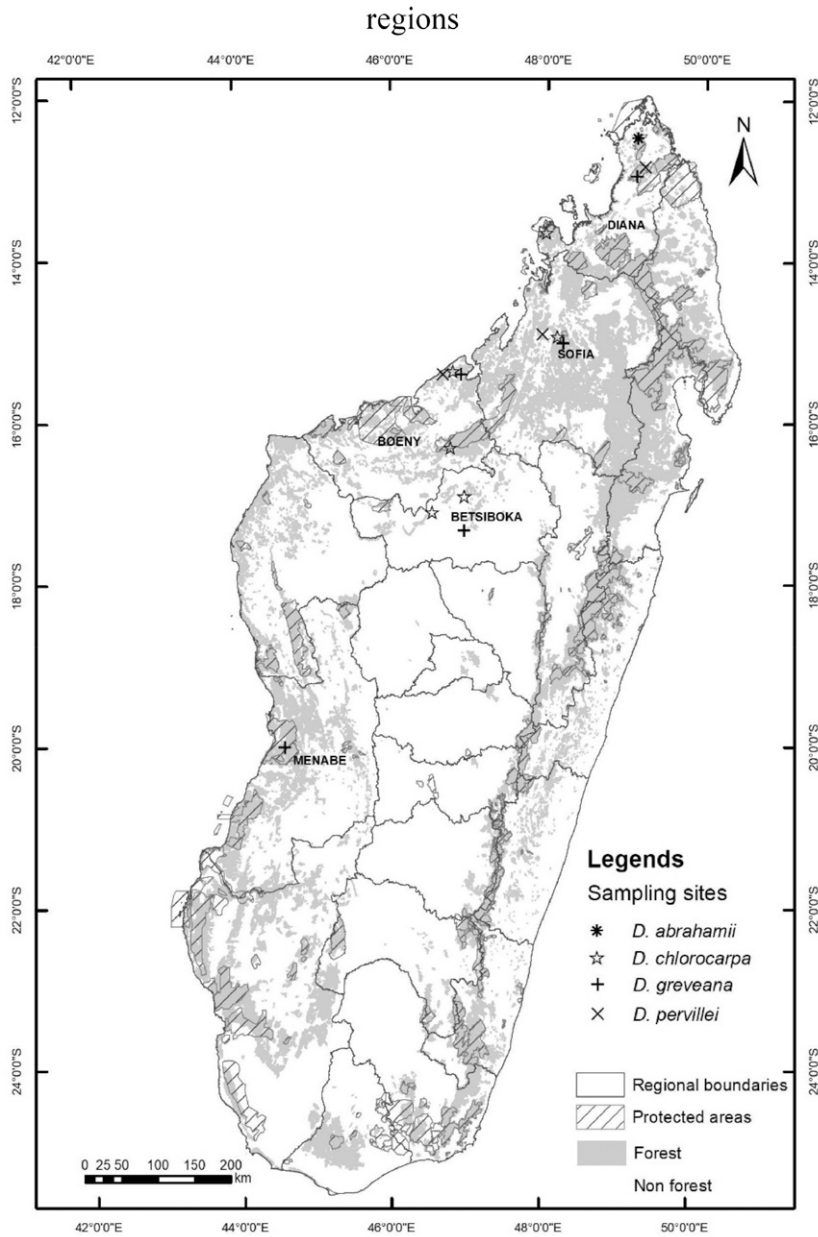
regions

Figure 1. Location of wood sampling sites in Diana, Sofia, Boeny, Betsiboka, and Menabe regions. Source: Institut Géographique et Hydrologique de Madagascar (FTM) BD500; Google Earth, 2020.
Geographic coordinate system: GCS International 1924.

$X_{\text{sample\_form} \times \text{wood\_type}}$ ($n \times p$) and a reference data $Y_{\text{sample\_form} \times \text{wood\_type}}$ ($n \times q$), where n, p, and q are respectively the number of spectra, independent variables (wavelengths), and species within a dataset.

Spectral Data Preprocessing

For each of the four spectral data, absorbances data in the wavelength ranges of 900-950 nm and 1650-1700 nm were removed from the raw

(a)   (b)
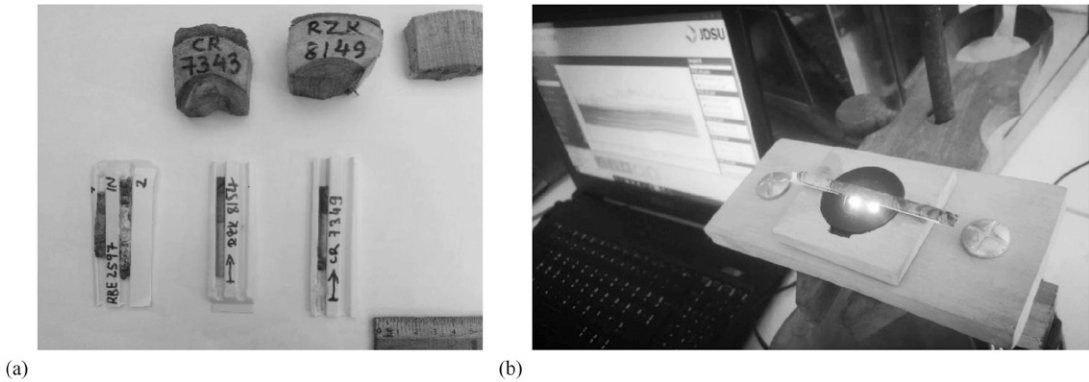
Figure 2.   Wood blocks and cores samples (a) belonging to the four *Dalbergia* species: *D. abrahamii* (RBE2597), *D. chloro-carpa* (CR7343, RZK8154), *D. greveana* (RZK8149, CR7349) and *D. pervillei* (SH748); (b) NIR absorbance spectra measurements on core wood sample using VIAVI MocroNIR 1700 spectrometer.

spectral data to eliminate noise. Several preprocessing methods were used to improve the signal including the first (SG1) and second (SG2) derivative followed by the Savitzky–Golay smoothing with filter width from 5 to 25 points by 2 points of steps, second-order polynomial Detrending (Dt) and Standard Normal Variate (SNV). A combination of two, then three of the different preprocessing methods was applied to the spectra.

Principal Component Analysis

Principal Component Analysis (PCA) was carried out separately on each of the four preprocessed datasets (Table 2) to evaluate the clustering of spectral data $X_{(n \times 113)}$ and their variation in the space defined by the Principal Components (PCs) according to the qualitative variables $Y_{(n \times 3)}$, the corresponding *Dalbergia* species. Outlier spectra were identified and removed on the basis of the Hotelling distance (T^2) and the PCA residuals (Q)

(Eriksson et al 2013) before the calibration of PLSDA models.

Partial Least Square Discriminant Analysis

The spectra were divided randomly into two datasets, 75% for training and 25% for validation, with the same proportionality of number of samples per species (Table 2). The PLSDA method was used based on the Non-Linear Iterative Partial Least Squares (NIPALS) algorithm for calibration (Wold et al 2001). Four PLSDA models were calibrated (Table 2): one model per combination of wood type (heartwood or sapwood) and sample form (wood block and core).

Each PLSDA model was calibrated with 20 Discriminant Variables (DVs). Due to the small number of available samples, Leave-One-OutCross-Validation (LOOCV) on the training datasets was used to select the best preprocessing methods and the optimal number of DVs

Table 1. Distribution of *Dalbergia* wood sample according to sample form and provenance from Madagascar.

Species	Number of samples (cores/blocks)	Region (cores/blocks)				
		Diana	Menabe	Sofia	Betsiboka	Boeny
D. abrahamii	9/–	9/–	–	–	–	–
D. chlorocarpa	16/14	–	–	1/–	1/–	14/14
D. greveana	16/17	4/1	1/–	2/–	3/–	6/16
D. pervillei	–/10	–/2	–	–/1	–	–/7

Table 2. Number and distribution of averaged spectra in the calibration and validation dataset according to species, sample form, sapwood, and heartwood.

Sample form	Wood type	Species	Spectral and reference data	Number of spectra		
				Calibration	Validation	Spectral outliers
Cores	Sapwood	*D. abrahamii*	$X_{cr \times spw} (39 \times 113)$	6	3	0
		D. chlorocarpa	$Y_{cr \times spw} (39 \times 3)$	11	4	0
		D. greveana		11	4	0
	Heartwood	*D. abrahamii*	$X_{cr \times hrt} (41 \times 113)$	6	3	0
		D. chlorocarpa	$Y_{cr \times hrt} (41 \times 3)$	12	4	0
		D. greveana		12	4	0
Blocks	Sapwood	*D. chlorocarpa*	$X_{blc \times spw} (38 \times 113)$	9	3	0
		D. greveana	$Y_{blc \times spw} (38 \times 3)$	13	4	0
		D. pervillei		7	2	0
	Heartwood	*D. chlorocarpa*	$X_{blc \times hrt} (21 \times 113)$	6	2	1
		D. greveana	$X_{blc \times hrt} (21 \times 3)$	5	2	0
		D. pervillei		4	2	0

cr, cores; blc, clocks; spw, sapwood; hrt: heartwood.

(Bertrand 2005). All data processing was performed using Chemflow (Rossard et al 2020).

The four most accurate PLSDA models according to wood type and sample form, which result from the optimal number of DVs and the best preprocessing methods were tested on the corresponding validation datasets. The classification results were shown in a confusion matrix Y, which is a *k* order square matrix generated by each discrimination model, where *k* is the number of species to be discriminated. The confusion matrix of each four models showed the predicted classes of the validation samples compared with their reference classes. A sample *i* is correctly classified if its predicted class $\hat{y}$ in the confusion matrix corresponds to its reference class *y*. The performance of each model was evaluated by precision, recall, and accuracy metrics defined as follows:

$$Precision = \frac{TP}{TP + FP}. \quad (1)$$

$$Recall = \frac{TP}{TP + FN}. \quad (2)$$

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN}. \quad (3)$$

Where TP, FN, TN, and FP are respectively the number of true positives, false negatives, true negatives, and false positives. For one reference class, TP measures the number of correctly classified samples, whereas TN explains the number of correct classifications of other classes. FP measures the number of incorrectly classified samples of the reference class, whereas FN is the incorrect classification of others. The Recall metric evaluates the classification rate, which is the ratio of correctly classified positive samples to the total number of actual positive samples. The precision expresses the probability of certainty of the correct classification, which is the ratio of correctly classified positive samples to the total number of positive classifications. The accuracy evaluates how good the model is to classify all the classes. It is the ratio of total number of correct classifications to the total number of classification results.

RESULTS

NIR Absorbance Spectra

Figure 3(a) and (b) show the SG1 (*W* = 7 points) mean spectra of *D. abrahamii, D. chlorocarpa, D. greveana*, and *D. pervillei* according to the wood type and the sample form.

Blocks spectra show higher absorption than cores spectra in the second harmonic region, regardless of the species or wood part. Absorption peaks at the vicinity of 1410, 1180, and 1350 nm regions
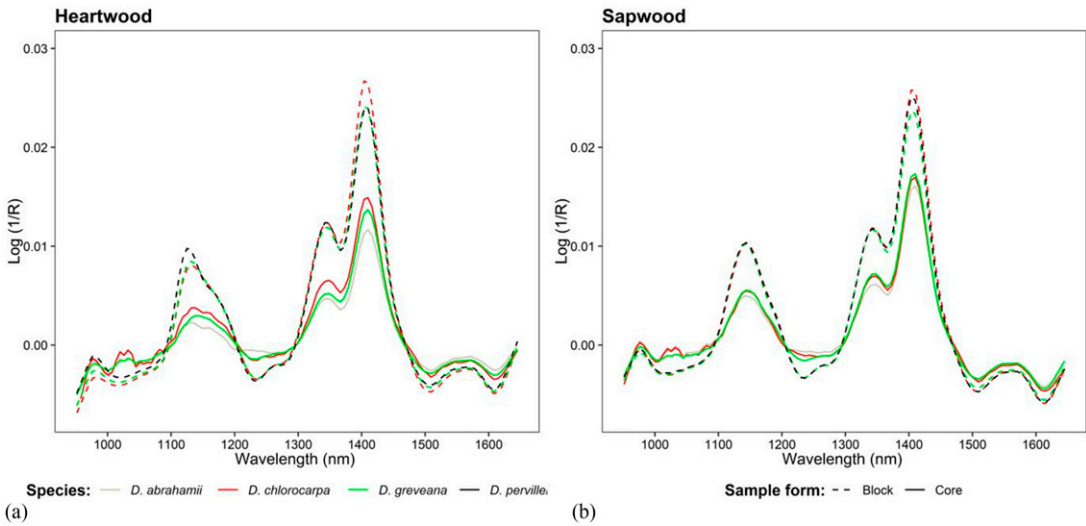
Figure 3.   Mean SNV + SG1 (*W* = 7) heartwood (a) and sapwood (b) spectra of the four *Dalbergia* species according to wood type.

were detected (Fig 3[a] and [b]) that are more important for blocks than cores. Core spectra were also noisier than blocks spectra, especially before 1100 nm.

Principal Components Analysis

Figures 4(a), 5(a), 6(a), and 7(a) show the PCA scores plots from the heartwood and sapwood

spectra of the blocks and cores samples in the PC1-PC2 space.

Separation between species is less significant based on sapwood than heartwood spectra (Fig 5[a], [b] and Fig. 7[a], [b]). For the heartwood of blocks, the preprocessing method based on the combination of the SG1 (*W* = 5 points), Dt, and SNV clustered spectra according to species in the PC1-PC2
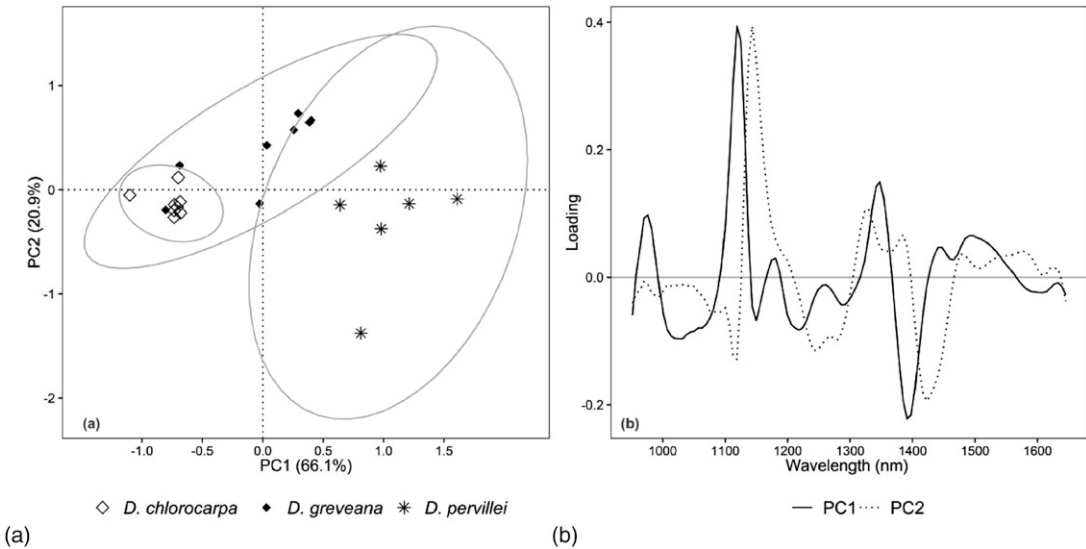

Figure 4.   PCA results from the SNV + Dt + SG1 (*W* = 5 points) heartwood spectra of blocks: (a) scores plot of the first two PCs and (b) corresponding loading plot.

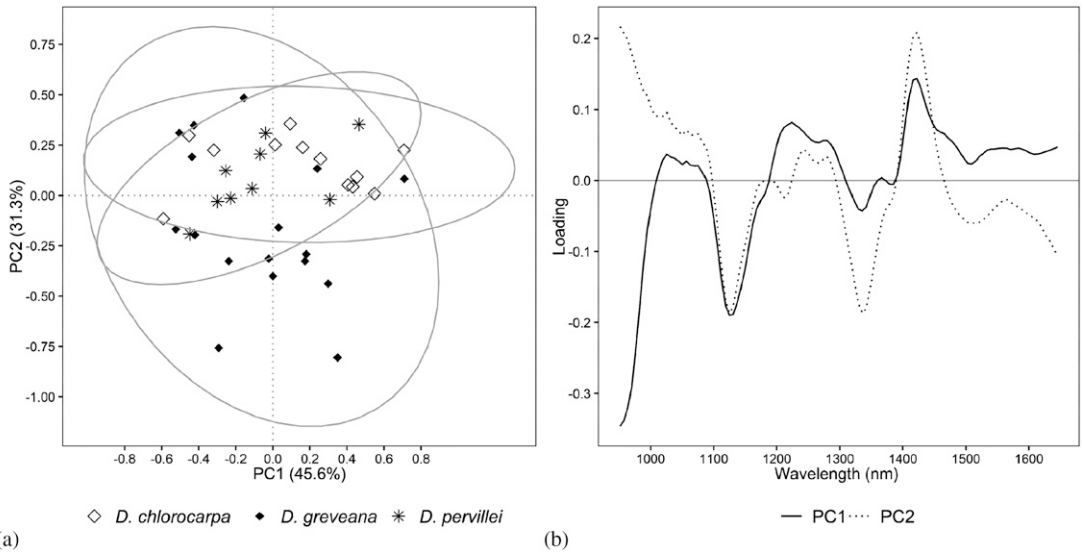(a)   (b)

Figure 5.   PCA results from the SG1 (*W* = 5 points) sapwood spectra of blocks: (a) scores plot of the first two PCs and (b) corresponding loading plot.

space (PC1 = 66.1%, PC2 = 20.9%) (Fig 4[a]). *D. pervillei* and *D. chlorocarpa* were clearly separated with a greater dispersion of *D. pervillei* spectra in the positive part of the PC1 axis (Fig 4[a]). The spectra of *D. greveana* were more scattered in

the PC1-PC2 space. The PC1 and PC2 loadings (Fig 4[b]) showed high contribution of the wavelength regions at the vicinity of 975, 1180, and 1250 nm to discriminate the three *Dalbergia* species, especially between *D. chlorocarpa* and *D.*
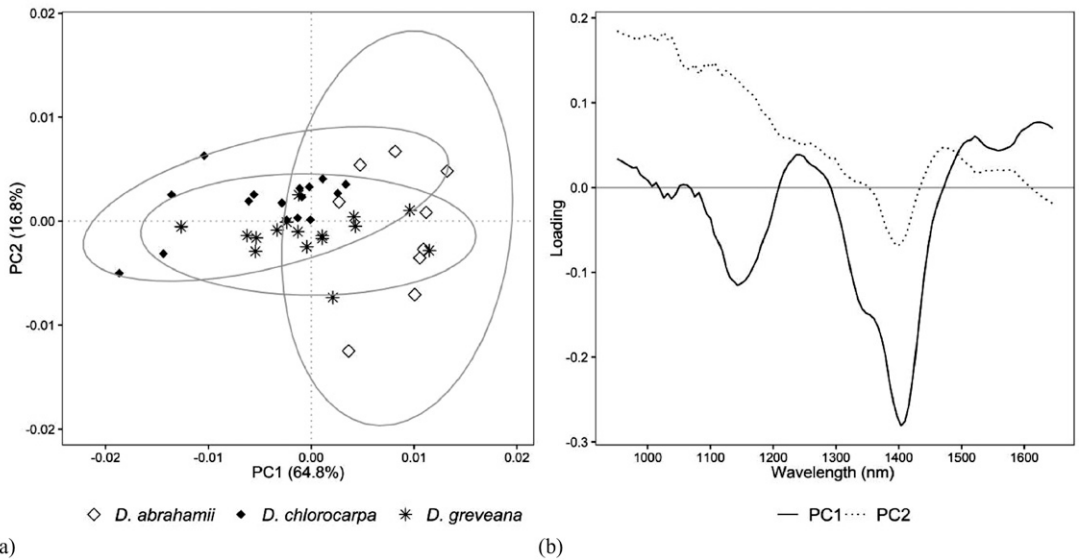

(a)   (b)

Figure 6.   PCA results from the SG1 (*W* = 11 points) heartwood spectra of cores: (a) scores plot of the first two PCs and (b) corresponding loading plot.
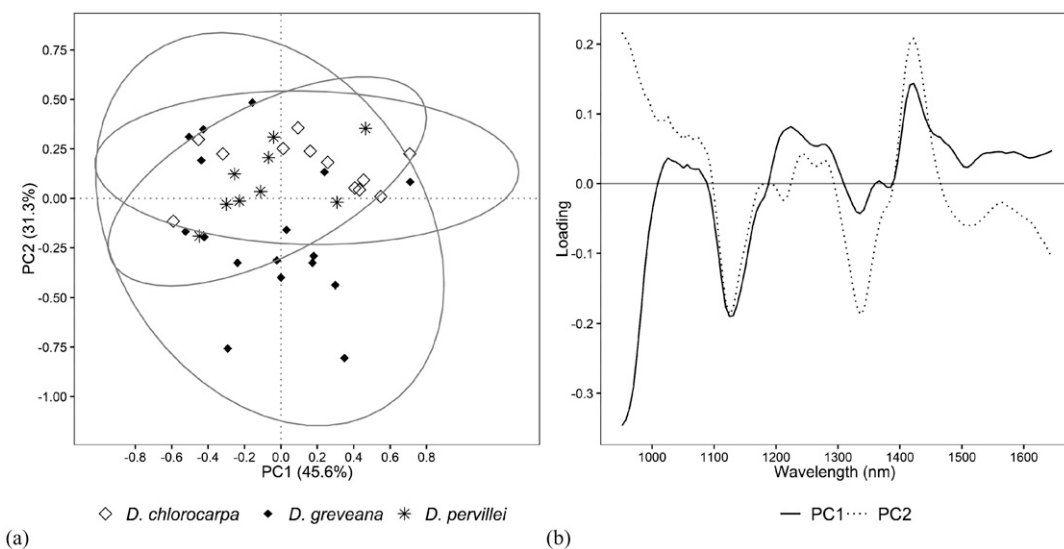
Figure 7. PCA results from the SG1 (*W* = 13 points) sapwood spectra of cores: (a) scores plot of the first two PCs and (b) corresponding loading plot.

pervillei, whose separation was significant. One sample of *D. chlorocarpa* was removed from the dataset because it had a high T^2 distance compared with the overall blocks' spectra (Table 2).

Spectra clustering according to species on the PCA score plot was less significant for the cores (Fig 6[a]) than blocks (Fig 4[a]). The use of the SG1 (*W* = 11 points) on the heartwood spectra of cores, however improved, the spectra clustering for the three species in PC1-PC2 space, which explains 81.6% of the spectral data variation (PC1 = 64.8%, PC2 = 16.8%) (Fig 6[a]). Several spectra of *D. abrahamii* and *D. chlorocarpa* were separated through PC1. *D. greveana* spectra were more scattered in the score plot. Corresponding loadings for PC1 and PC2 highlighted the contribution of the wavelength regions in the vicinity 1250 nm, and 1450 nm (Fig 6[b]) to discriminate the three species.

Partial Least Squares Discriminant Analysis

The performance of the preprocessing methods varies depending on the PLSDA models (Table 3). The SNV combined with the SG2 resulted in a higher accuracy in cross-validation for core PLSDA models. The addition of the Dt resulted

in a higher discrimination accuracy in cross-validation for block PLSDA (Table 3). The optimal number of DVs corresponding to the highest correct classification rate in cross-validation ranged from 3 to 11 DVs.

The four *Dalbergia* species can be better discriminated from their heartwood spectra. Of the two heartwood models, the PLSDA$_{(Block \times heartwood)}$ show the higher accuracy of 83.3%. All samples of *D. chlorocarpa* and *D. pervillei* were well-classified. PLSDA$_{(Block \times heartwood)}$ classified *D. pervillei* with precision and recall of 100%. This finding shows that *D. pervillei* can be accurately separated from *D. chlorocarpa* and *D. greveana* from the heartwood spectra of blocks. The precision of the classification when the model identifies *D. chlorocarpa* is 67% because of a misidentification of a *D. greveana* sample, which was classified as *D. chlorocarpa* (Table 4[b]).

The PLSDA$_{(Core \times heartwood)}$ showed an accuracy of 81.8% (Table 3). All *D. chlorocarpa* samples were well-classified with recall of 100%. One sample of *D. abrahamii* and one sample of *D. greveana* were misclassified as *D. chlorocarpa* (Table 5), decreasing the precision of classification at 67% when the model identifies *D. chlorocarpa*.

Table 3. Discrimination and classification results of the four *Dalbergia* species according to the four PLSDA models.

PLSDA model names	Best preprocessing method	Number of DVs	LOOCV	Classification results		
				Accuracy	Precision	Recall
PLSDA (Block × Heartwood)	–	–	–	–	–	–
D. chlorocarpa	SG1 + Dt + SNV	5	86.70	83.30	0.67	1.00
D. greveana	–	–	–	–	1.00	0.50
D. pervillei	–	–	–	–	1.00	1.00
PLSDA (Block × Sapwood)	–	–	–	–	–	–
D.chlorocarpa	SG1 + Dt + SNV	3	65.50	77.80	0.75	1.00
D. greveana	–	–	–	–	0.75	0.75
D. pervillei	–	–	–	–	1.00	0.50
PLSDA (Core × Heartwood)	–	–	–	–	–	–
D. abrahamii	SG2 + SNV	3	76.70	81.10	1.00	0.50
D. chlorocarpa	–	–	–	–	0.67	0.10
D. greveana	–	–	–	–	1.00	0.60
PLSDA (Core × Sapwood)	–	–	–	–	–	–
D. abrahamii	SNV + SG2	14	62.10	72.20	0.75	0.60
D. chlorocarpa	–	–	–	–	0.67	0.80
D. greveana	–	–	–	–	1.00	0.40

PLSDA, Partial Least Square Discriminant Analysis; DVs, Discriminant Variables; SNV, Standard Normal Variate.

For *D. chlorocarpa*, which were common to the blocks and cores, classification results at species level were consistent for the four PLSDA models. Precisions of classification were between 67% and 75% while recall values were between 80% and 100% (Table 3).

DISCUSSION

PLSDA Model Accuracy According to Wood Type

The PCA score plot (Figs 4-7) showed that heartwood spectra from blocks and cores clustered more tightly according to species than sapwood spectra. This trend was confirmed by the PLSDA results, which also had better discrimination of species when using heartwood spectra. The need for a low number of DVs for heartwood PLSDA models (Table 3) also explains why it is easier to separate these four species using heartwood spectra.

In terms of factor inherent to the chemistry of wood, this good separation could be explained by the number of extractives, which are significantly higher in heartwood than sapwood (Morais and Pereira 2012; Razafimahatratra et al 2019), and which also vary among species (Freire et al 2005). The separation of the *Dalbergia* species studied here are consistent with the work of others who obtained discrimination results above 80% from heartwood spectra of non-Malagasy *Dalbergia species* using a portable and handheld NIR Spectrometer (Snel et al 2018).

Table 4. Confusion matrix from the validation of the two wood blocks PLSDA models for *Dalbergia* species discrimination ([a] for sapwood samples, [b] for heartwood samples).

	Reference class (sapwood)			Number of well-classified samples	Reference class (heartwood)			Number of well-classified samples
	D. chlorocarpa	*D. greveana*	*D. pervillei*		*D. chlorocarpa*	*D. greveana*	*D. pervillei*	
Predicted classes								
D. chlorocarpa	3	1	–	3	2	1	–	2
D. greveana	–	3	1	3	–	1	–	1
D. pervillei	–	–	1	1	–	–	2	2
Accuracy (%)	–	–	–	77.8	–	–	–	83.3

Table 5. Confusion matrix from the validation of the two wood cores PLSDA models for species discrimination of (a) sap-wood and (b) heartwood.

	Reference classes (sapwood)			Number of well-classified samples	Reference classes (heartwood)			Number of well-classified samples
	D. abrahamii	*D. chlorocarpa*	*D. greveana*		*D. abrahamii*	*D. chlorocarpa*	*D. greveana*	
Predicted classes								
D. abrahamii	3	1	–	2	2	–	–	2
D. chlorocarpa	–	4	2	4	1	4	1	4
D. greveana	–	–	2	2	–	–	3	3
Accuracy (%)	–	–	–	72.7	–	–	–	81.8

Effect of the Sample Form (Blocks vs Cores) on NIR Absorbance Spectra and PLSDA Models

Block spectra generally showed a higher absorbance than core spectra. This could be due to the difference in sample size for the two sample forms. Unlike blocks, the surface of cores was not flat but curved, which could change the focal area for NIR measurements. The diameter of cores was also not large enough to cover the entire measurement window of the MicroNIR spectrometer resulted in some random noise on the core spectra. The SG1 ($W = 5$ points) spectra of the two sample forms had indeed made it possible to highlight more intense absorbance peaks on flat than curved wood surface. Some random noise was also generated by the effect of external stray light on the core spectra. The absorbance spectra of the blocks could then be more faithful than those of the cores.

Other effects related to the wood sample probably came from the difference in surface state of the two sample forms because block samples have smoother surfaces than cores. Previous studies have shown that the presentation and preparation of the samples strongly influence the performance of the models (Hein et al 2010). Zhang et al (2015) also showed that the absorption of NIR radiations by wood samples decreases with increasing surface roughness, and it could influence the performance of NIR calibration models.

PLSDA models based on blocks were calibrated from the spectra measured on the wood transversal face, unlike the core PLSDA models that were calibrated from the spectra collected on unidentified faces between radial and transversal. The SG1

spectra showed more intense peaks for the blocks than the wood cores around 1200 nm, which are dominated by the second overtone of O-H and N-H bonds in the lignin and cellulose component of the wood, and 1470 nm region which corresponds to the first overtone of O-H bonds in the hemicelullose (Schwanninger et al 2011). NIR spectra of the blocks, which were collected only on the transversal face of wood, thus provided more chemical information. Costa et al (2018) also highlighted that NIR spectra of the wood transversal face are different from those of the radial and tangential surfaces due to the difference in anatomical arrangement of cells in the three wood sections. According to Braga et al (2011), models calibrated on a given wood face should not be used to analyze spectra obtained on another wood face.

Ability of the Portable and Handheld MicroNIR Spectrometer on *Dalbergia* Species Discrimination

The NIR wavelength range covered by the Micro-NIR (900-1700 nm) is smaller than that of bench-top spectrometers used in the literature. Chemical compounds with covalent bonds whose vibrational frequencies are outside the wavelength range of 900-1700 nm could, however, be useful for better species discrimination (Pastore et al 2011; Snel et al 2018). For example, Snel et al (2018) discriminated seven CITES appendix *Dalbergia* species using a portable microPHAZIR RX spectrometer (Thermo Scientific, Boston, MA) covering 1595-2396 nm with a discrimination accuracy of 90%. A portable instrument covering the entire NIR range may therefore provide additional discrimination power.

Use of NIR Spectroscopy for a Sustainable Management of Forest Resources

This study demonstrates the potential of the portable MicroNIR as a tool for supporting sustainable management and trade of *Dalbergia* tree species of Madagascar. Handheld spectrometers are accessible resources for developing countries like Madagascar as they are affordable and can be used to enforce the national law against trafficking and illegal trade of precious woods. Advantageously, once the models have been calibrated, the identification process by NIR Spectroscopy is fast and requires minimal science background for classification of unknowns. Future studies should investigate model recalibration with more samples in the training set, the effects of the external parameters, such as wood water content and surface aging of the wood on the discrimination models, and including more trade-significant species.

CONCLUSIONS

This study demonstrates the identification of Malagasy *Dalbergia* with a portable NIR Spectrometer. Significantly, this study showed discrimination within a genus, where there is less anatomical variation than between genera. Discrimination results from heartwood PLSDA using flat surface wood with full spot size were the most accurate. However, using wood core samples with round surface is less invasive. The correct classification rates for *D. greveana* and *D. abrahamii* were generally lower than those of *D. pervillei* and *D. chlorocarpa*. Some perspectives, such as the recalibration of PLSDA models, with more wood samples covering the natural variability related to wood chemical properties for the 58 Madagascar *Dalbergia* species that are potentially harvestable, as well as the testing of the models on samples completely independent of the training set are important to develop MicroNIR as a tool to assist in the identification of Madagascar's *Dalbergia* species. Due to its rapidity and portability, the availability of handheld NIR Spectrometer for forest law enforcement officers and custom officials is of crucial interest to support CITES in the management and sustainable trade of these resources. In-depth research on the external variables, which affect the performance of the models for on-field identification, must also be carried out to understand the accuracy limits of NIR Spectroscopy to use the tool to fight against illicit trafficking of the valuable wood species of Madagascar. Taxonomic clarification of Madagascar's *Dalbergia* with the objective of establishing a stable reference database must also be pursued.

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