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NEAR INFRARED SPECTROSCOPY FOR SEPARATION OF TAUARI WOOD IN BRAZILIAN AMAZON NATIVE FOREST

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This work aimed to characterise different wood species known as tauari using the near infrared spectroscopy (NIR) as a support tool for identification. The spectra were obtained in a Tensor 37 spectrometer in the range of 4000–10000 cm^{-1}, using 35 samples of solid wood from four different species with 21 different origins. Specimens measuring 2.5 centimeters long were extracted from each sample. The spectra were obtained on all faces of the samples and the analysis was performed in three different situations: i) sample mean, ii) only cross-sectional spectra and iii) only longitudinal (tangential and radial) spectra. The classification methods tested were linear discriminant analysis combined with principal component analysis (PCA-LDA). The best pretreatment was the second derivative, highlighting *Couratari guianensis* species with accuracy ranging from 55.6 to 61.1%. The LDA classification, based on information from the NIR spectra, showed greater discriminatory potential for the species. However, due to the complexity of the separation of the tauari wood, the use of near-infrared (NIR) spectroscopy together with the anatomical identification is suggested, for confirmation of the species.

Keywords: *Couratari* spp., spectroscopy, spectral curves, Embrapa, Walter A. Egler collection

INTRODUCTION

The Brazilian Amazon has many tropical arboreal species that are attractive to the wood industry. These are often exploited illegally, contributing to the increase in deforestation index (Soares et al. 2017). The Amazon biome is important in this scenario because it represents 49.3% of Brazilian territory, with 13,375 catalogued species, of which 2,046 (15.4%) are endemic to the country (Forzza et al. 2012, SFB 2013). Many species that produce wood of commercial value are similar even at the microscopic level (Soares et al. 2017).

In general, for forest species identification, reproductive and vegetative material is used, but for wood-producing species, characterisation based on anatomical characteristics is necessary, which is time consuming and needs specialists to obtain adequate results. So, new nondestructive techniques must be tested and refined to obtain more agility, practicality and precision in Amazon wood identification. One possibility is near-infrared (NIR) spectroscopy, which is being successfully applied as a nondestructive method in the wood industry, with satisfactory quality analysis. In the past few years portable equipment has become available (Pastore et al. 2011, Bergo et al. 2016).

The NIR analysis of material with high moisture content, such as wood, is normally associated with statistical procedures that help identification and classification of the traits of interest, together with chemometrics, which involves mathematical procedures to derive significant chemical information from samples with high complexity, allowing the extraction of relevant data from the analysed material (Tsuchikawa & Kobori 2015).

The NIR, in combination with multivariate analyses, carry information from various functional groups such as cellulose, hemicellulose, lignin and wood extractives present in wood (Tsuchikawa 2007). The NIR spectrum is a complex material consisting of a set of bands formed by the overlap of various vibrational transitions in the region of overtones and band combinations, which requires the establishment of a mathematical model that relates the obtained spectra with one or more properties of interest, either quantitatively or qualitatively, depending on the objective or chemometric method employed, of a sample under routine analysis (Pasquini 2003).

This technique enables measurements of light and sample interaction, which is the result of chemical vibration from constituents, and one reading can be performed in 90 seconds on average (Magalhães et al. 2005). Wood processing industries need fast methods, such as NIR analysis, that also enable more reliable species identification and classification (Yang & Evans 2003). Many species with visually similar characteristics are present in commerce and can be distinguished by NIR analysis, such as *Carapa guianensis*, *Cedrela odorata* and *Micropholis melinoniana* (Pastore et al. 2011).

In the tropical wood trade, the group known as tauari comes from distinct tree species of the Lecythidaceae family, with similar characteristics (ITTO 2005). The trees have medium to high stature and are frequently found in the upper strata of lowland forests (Souza & Lorenzi 2005). Its wood is moderately easy to cut and has good finish. It is widely used in civil construction, with demand in the national and international markets (Bernal et al. 2011, Paula & Costa 2011). One problem is the difficulty of species discrimination. This is aggravated by the use of diverse vernacular names, making it hard to identify the species (Martins et al. 2003).

Thus, based on the importance of the tauari group and the difficulties of its identification, this study analysed wood samples from different species with NIR spectroscopy as a tool to support wood distinction.

MATERIALS AND METHODS

The study evaluated 36 wood samples known popularly as tauari, of four distinct species. The samples consisted of 18 specimens from scientific collections: nine from the Walter A. Egler Collection of Emilio Goeldi Paraense Museum (six *Couratari guianensis*, two *C. stellata* and one *C. oblongifolia*), and nine from Embrapa Amazônia Oriental, Pará state (four *Couratari guianensis*, two *C. stellata*, two *C. oblongifolia* and one *C. multiflora*) (Table 1). The materials are registered at the *Conselho de Gestão do Patrimônio Genético* (CGEN/SISGEN) as ADE10D5.

Table 1 Samples of tauari wood from Walter A. Egler Collection of Emilio Goeldi Paraense Museum and Embrapa Amazônia Oriental

Species	Registration	Origin of sample
Couratari stellata	2532-MGW	Suriname
Couratari stellata	4468-MGW	Roraima
Couratari oblongifolia	5399-MGW	Monte do Jari-PA
Couratari guianensis	3437-MGW	Tucuruí-PA
Couratari guianensis	5648-MGW	Rio Sororo-PA
Couratari guianensis	6348-MGW	Roraima
Couratari guianensis	1981-MGW	Suriname
Couratari guianensis	2462-MGW	Suriname
Couratari guianensis	2907-MGW	Amapá-AP
Couratari stellata	1790-IAN	Santarém-PA
Couratari stellata	1792-IAN	Santarém-PA
Couratari guianensis	6734-IAN	Rio Juruá-PA
Couratari guianensis	7812-IAN	Vila Santa Izabel-PA
Couratari guianensis	7534-IAN	Novo repartimento-PA
Couratari guianensis	1718-IAN	Santarém-PA
Couratari oblongifolia	6752-IAN	Paragominas-PA
Couratari oblongifolia	1774-IAN	Santarém-PA
Couratari multiflora	1767-IAN	Rio Amazonas

MGW = Walter A. Egler Collection, Emílio Goeldi Paraense Museum, IAN = Embrapa Amazônia Oriental

For complementation, 18 samples with dimensions of 50 × 20 × 5 cm (length, width and thickness) were collected randomly from 15 sawmills in 10 municipalities in Pará. Species identification was carried out in the Wood Anatomy and Quality Laboratory (LANAQM) at Federal University of Paraná (UFPR), Paraná state, Brazil. The sampling of the individuals in this research covered all the radial trunk variation, so there was no separation between heartwood and sapwood.

A microscopic characterisation was based on standards from the International Association of Wood Anatomists (IAWA 1989), and macroscopic was based on INTKEY interactive key of general and macroscopic characteristics of commercial woods from Brazil (Coradin et al. 2011). After anatomic characterisation, 18 samples were identified as from the Lecythidaceae family, composed of four species: six *Couratari stellata,* seven *C. oblongifolia,* four *C. guianensis* and one *Eschweilera* sp. (Table 2).

The NIR spectra were collected using a Tensor 37, equipped with an integrating sphere and operating in reflectance mode, in a spectral range of 4000–10000 cm^{-1}, with resolution of 4 cm^{-1} and 64 scans. Spectra were obtained from all surfaces of 35 samples and divided into transversal and longitudinal (radial and tangential) sections. Six spectra were collected from each surface, 18 spectra per sample for a total of 630 spectra from all the tauari species. Materials were stored at controlled atmosphere with temperature of 25 ± 2 °C and relative humidity of 60 ± 2%.

The analysis and model construction were carried out based on data from the Walter A. Egler Collection and Embrapa Amazônia Oriental. External classification and identification were carried out with samples collected from sawmills in Pará. Data analysis was performed with Unscrambler X (version 10.1) in original form (raw data) and with second derivative values from Savitzky-Golay smoothing (polynomial order = 2, smoothing points = 15).

The influence of the wood section from which the spectra were collected for species discrimination was also evaluated: i) mean value of sample, ii) mean value only of transversal surface of samples and iii) mean value only of longitudinal surface (radial and/or tangential) of samples.

The classification method applied was linear discriminant analysis (LDA) based on principal component analysis scores (PCA-LDA). The PCA was performed based on the Nonlinear Iterative Partial Least Squares (NIPALS) algorithm with mean centered data and cross validation. In model construction, some divergence was

Table 2 Samples collected in sawmills in Pará state and identified based on macro and microscopic characteristics of wood, by municipality

Municipality (origin)	Species	Number of samples identified
Altamira	*Couratari stellata*	1
	Couratari oblongifolia	2
	Eschweilera sp.	1
Uruará	*Couratari oblongifolia*	1
	Couratari stellata	3
Novo Progresso	*Couratari stellata*	1
	Couratari guianensis	1
Goianésia	*Couratari guianensis*	1
Maracajá	*Couratari guianensis*	1
Paragominas	*Couratari guianensis*	1
Anapú	*Couratari stellata*	1
	Couratari oblongifolia	1
Tailândia	*Couratari oblongifolia*	1
Pacajá	*Couratari oblongifolia*	1
Breu Branco	*Couratari oblongifolia*	1
Total		18

observed between samples from the Walter A. Egler Collection and Embrapa Amazônia Oriental. Thus, only data from the Embrapa samples were applied for external classification because the region where the material was collected was nearest to the sawmills.

RESULTS AND DISCUSSION

Mean NIR spectra of species collected from sawmills in Pará, spectral range of 4000–10000 cm^{-1}, showed similarity and different intensity of absorbance (Figure 1). The species *C. stellata*, *C. oblongifolia* and *Eschweilera* sp. were more similar, and *C. guianensis* showed some divergence in baseline, principally in the region 5020–5473 cm^{-1}. Li et al. (2019), studying a new pretreatment methods for Vis-NIR calibration modeling of air-dry density of *Ulmus pumila* wood, observed that the density and the spectrum vary according to the transformation method. Literature shows the influence of water in the region of 5051 cm^{-1} and bands from 5150–5220 cm^{-1}, presence of hemicelluloses at 5236 cm^{-1} and 5245 cm^{-1}, and also semi-crystalline or crystalline region of cellulose at 5464 cm^{-1} (Schwanninger et al. 2011).

To verify grouping formation, PCA was performed with mean second-derivative spectra of species by origin (Figure 2), i.e., with mean data for each sample collected from different municipalities of Pará. The second derivative was used as the best pretreatment because the main objective of this analysis was to make the dataset more homogeneous, in order to reduce the sources of non-informative variations and consequently improve the signal/noise ratio, making future matrices more conditioned to modeling (Rinnan et al. 2009, Souza and Poppi 2012).

In general, visual similarity of species and origin was observed. Some divergence occurred principally for *C. guianensis*, for which it was observed that the species had more influence on the grouping than the origin. The use of second derivative data for wood discrimination with adequate results has been reported for timber of various origins, as well as pine species and species named angelim, in Brazil (Sandak et al. 2011, Zhang et al. 2014, Horikawa et al. 2015, Hwang et al. 2016, Muñiz et al. 2016).

Two principal components explained 92% of the total variation of NIR with the second derivative data. All species from Altamira were similarly close. All *C. stellata* from Uruará were grouped, and *C. stellata* from Novo Progresso was grouped with *C. oblongifolia* from Uruará. Samples from *C. guianensis* collected in Goianésia, Maracajá and Paragominas were grouped. Samples from Anapú, *C. stellata* and *C. oblongifolia* were also grouped, and samples of *C. oblongifolia* obtained from Anapú, Breu Branco, Pacajá and Tailândia were in the same quadrant. The results were probably related to edaphoclimatic and forest conditions. Also, materials were collected from sawmills without identification of its origin, which poses a problem since trees are often felled in one place and the logs are taken to sawmills in different municipalities.

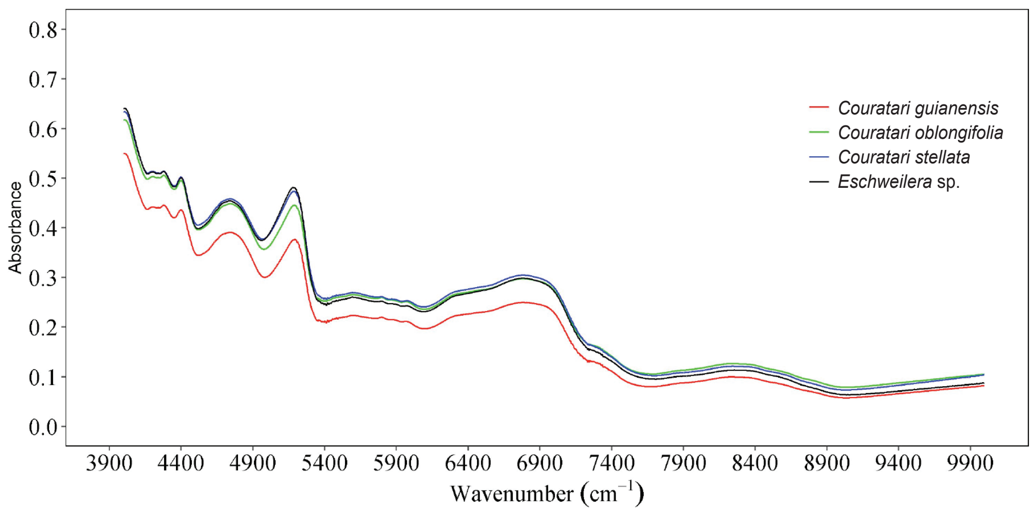

Figure 1 Mean NIR spectra of tauari species collected from different municipalities of Pará state

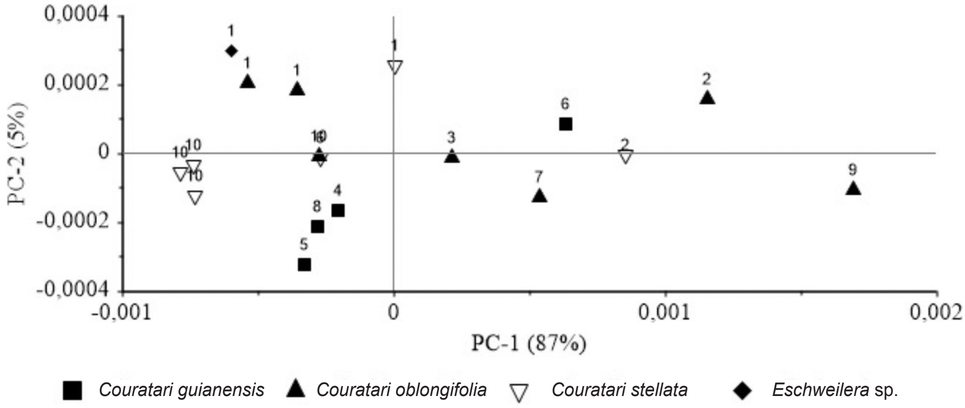

Figure 2 Score graph from principal component analysis (PCA) with mean second-derivative near-infrared (NIR) spectra of 'tauari' species collected from different municipalities of Pará state: 1 - Altamira, 2 - Anapú, 3 - Breu Branco, 4 - Goianésia, 5 - Maracajá, 6 - Novo Progresso, 7 - Pacajá, 8 - Paragominas, 9 - Tailândia, 10 – Uruará

The origin of each species can influence wood quality, principally physical and mechanical properties (Gonçalez et al. 2009). Characteristics such as nutrient availability, physical properties and carbon content in soil can also influence tree growth and wood properties (Fageria 2012). The NIR spectroscopy is influenced by these factors. Sandak et al. (2011) described relations between spectra and origin of trees in Europe. Nisgoski et al. (2016) related the sensitivity of NIR in distinguishing origins of *Cryptomeria japonica*. Hwang et al. (2016) verified the application of the technique in pine species from different countries. Nisgoski et al. (2018a) observed the influence of toposequence position on NIR spectra of *Stryphnodendron adstringens*.

Evaluating the loading graph (Figure 3), it was possible to verify the regions with more influence in distinguishing 'tauari' wood species. Wavenumbers from 5974–5774 cm^{-1}, bands at 5599 cm^{-1}, bands at 4904 cm^{-1}, region from 4424–4391 cm^{-1}, wavenumber at 4366 cm^{-1}, and region from 4349–4090 cm^{-1} were related to all cell wall components (cellulose, hemicelluloses and lignin). Other authors have observed variation in the use of total spectra or regions for wood identification. Pastore et al. (2011) described the wavenumbers from 4249 cm^{-1} to 6100 cm^{-1} as the most informative in separation of species similar to mahogany. Bergo et al. (2016) correctly classified samples of mahogany from 27 countries in the region from 5547 cm^{-1} to 6897 cm^{-1}. Muñiz et al. (2016) indicated that regions in 4000–5000 cm^{-1} and 5500–6200 cm^{-1} are adequate for discrimination of wood species of the angelim group. Nisgoski et al. (2016) observed that bands from 4000 to 6200 cm^{-1} were adequate for separating six origins of sugi. Toscano et al. (2017) verified the influence of wavenumbers from 4000 to 7500 cm^{-1} in separation of hardwood and softwood, and pine, fir and beech. On the other hand, Hwang et al. (2016) applied spectra from 4000 to 8000 cm^{-1} to identify pinus species.

The influence of the surface where the spectra were obtained for tauari species collected in different municipalities of Pará state were investigated separately with transversal sections (Figure 4A) and longitudinal sections (Figure 4B). All graphs showed similar behavior, where there was no evidence of a more important section for inspection. For *C. guianensis*, three samples formed a group and others were more distant. For *C. oblongifolia,* the samples did not show a strong clustering tendency, being influenced by origin. For *C. stellata*, samples from the same location were grouped and other samples were distributed irregularly.

The similarity between the sections may be related to anatomical features. Muñiz et al. (2016), showed that the cross sections bring more information, mainly about vessels, parenchyma, fibers and ray cells, than longitudinal sections (radial and tangential). The influence of section in species discrimination was also evaluated by Nisgoski et al. (2018b) in Caatinga species. The authors commented that in cluster analysis, mean spectra of samples or longitudinal sections

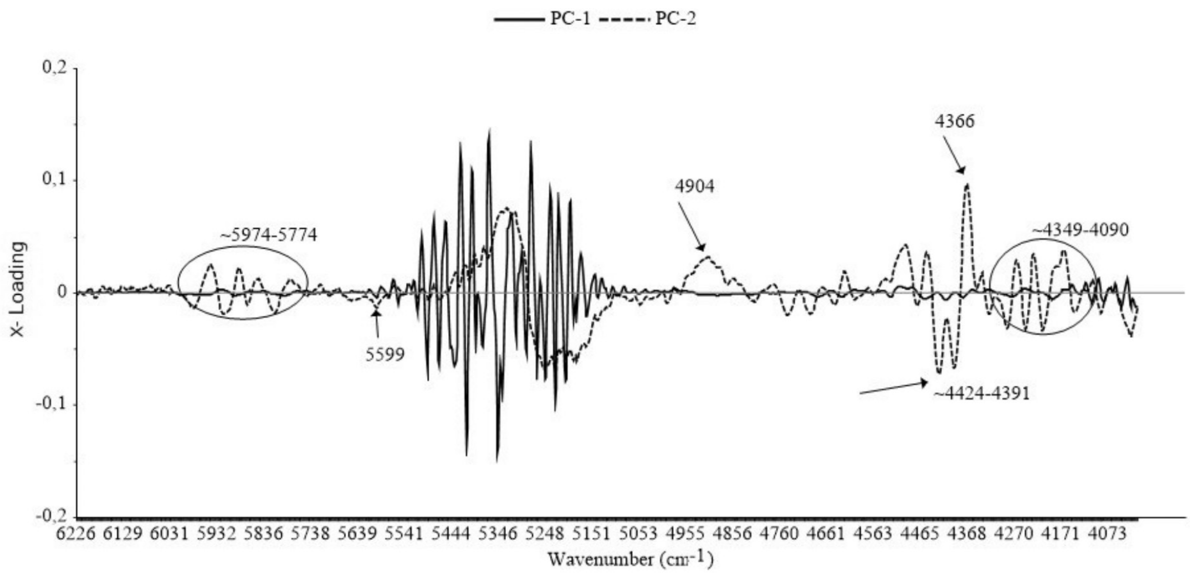

Figure 3 Factor loading graph of principal component analysis (PCA) with mean second-derivative near-infrared (NIR) spectra from tauari species collected from different municipalities of Pará state

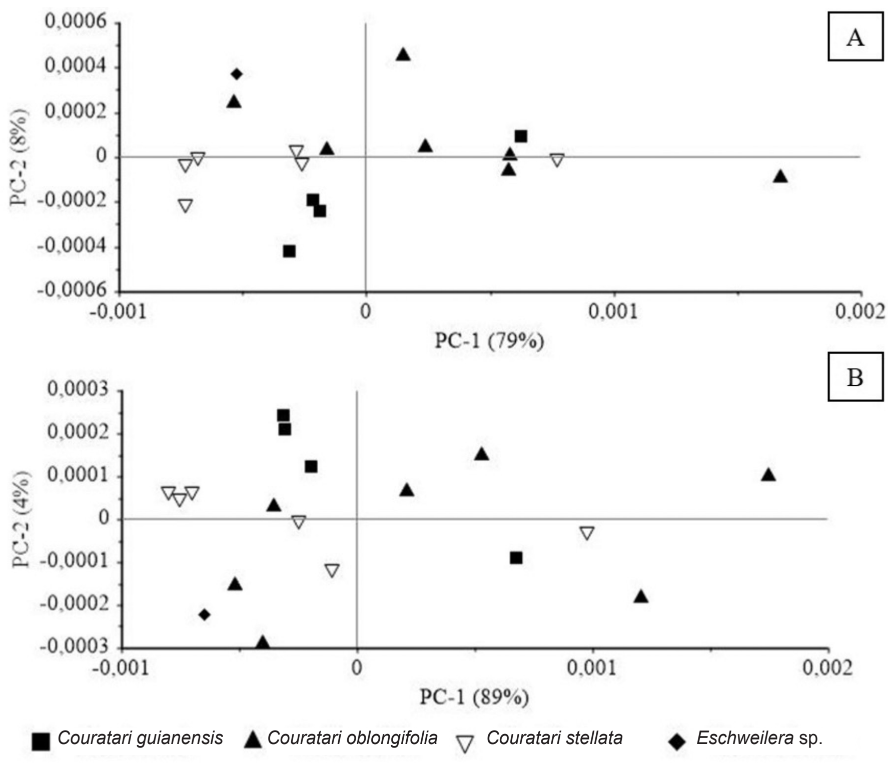

Figure 4 The principal component analysis (PCA) for second-derivative, near-infrared (NIR) spectra of tauari species collected in different municipalities of Pará state; (A) mean of transversal sections; (B) mean of longitudinal sections

were more suitable. However, for external classification, all sections showed power for species discrimination, which is important for practical applications.

The species *C. guianensis, C. oblongifolia* and *C. stellata* from the Walter A. Egler Collection and Embrapa Amazônia Oriental, and were also collected from sawmills in different regions of

Pará state. Thus, PCA was performed to verify the grouping of species based on time of storage (Figure 5). The origin of the material had more influence, but the species remained isolated.

The analysis based on NIR spectra for monitoring wood weathering and analysis of archeological wood and chemical composition of historical wood are reported in the literature (Sandak et al. 2009, Sandak et al. 2010). Other authors have also commented that NIR spectroscopy is useful to ascertain changes in molecular degradation of wood (Inagaki et al. 2009). Thus, material can be applied for species identification independent of storage time.

Principal component analysis-linear discriminant analysis (PCA-LDA) classification of near-infrared (NIR) spectra

In model determination with NIR spectra for tauari species of samples from scientific collections, great divergence were observed between data from Walter A. Egler Collection and Embrapa Amazônia Oriental. Thus, to construct a model for external classification or identification of material obtained from different municipalities of Pará state, only spectra from Embrapa specimens were used. This was also because the samples came from regions near the sawmills.

Table 3 shows the percentage of total classification of samples collected in Pará state. Data included correct and incorrect results, showing the tendency of the model. The longitudinal surface spectra classified samples as *C. multiflora*, a species not identified anatomically. These results confirmed the similarity between all species of the genera *Couratari*. Since no sample of *Eschweilera* was included in constructing the model, the sample was incorrectly classified as genus *Couratari*.

The best results for classification of samples are shown in Table 4. It was possible to verify a difference based on pretreatment (second derivative), wavenumber (all or bands in the region 4000–7500 cm^{-1}) and section where spectra were collected. These influenced species discrimination, as did intrinsic characteristics of species. In principle, PCA-LDA could provide good information for distinguishing *C. guianensis* from *C. oblongifolia* and *C. stellata*, regardless of section or wavelength.

Wood from the tauari group is similar to that of other genera of the Lecythidaceae family, and very hard to identify to the species level (Procópio & Secco 2008). The material applied to calibrate the model was from scientific collections, submitted to varying storage times, with possible residues from preservatives, and without identification of age or position in the tree. All of these characteristics can change the chemical makeup of samples and influence NIR spectra. Even so, results indicated the technique's potential for identifying wood samples marketed as tauari.

The PCA-LDA classification has been shown to be adequate for wood identification, such as angelim and caatinga species, with variation in wavenumbers and sections with better results, indicating the predominance of individual

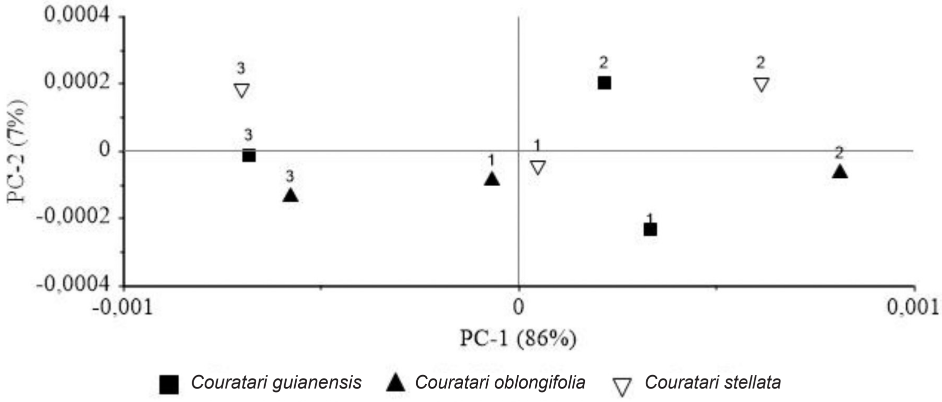

Figure 5 PCA with second-derivative spectra for species obtained from the Walter A. Egler Collection of Emilio Goeldi Museum, Embrapa Amazônia Oriental and from sawmills in different municipalities of Pará state: (1) Pará state, (2) Embrapa, (3) museum

Table 3 Percentage of total classification of 18 samples of species collected in Pará state based on near-infrared (NIR) model using Embrapa specimens, correct or incorrect

NIR spectra	*C. guianensis*	*C. multiflora*	*C. oblongifolia*	*C. stellata*
Mean of all sections				
Raw 4000–10000 cm^{-1}	11.1%	-	33.3%	55.5%
2nd derivative 4000–10000 cm^{-1}	61.1%	-	38.9%	-
Raw 4000–7500 cm^{-1}	11.1%	-	50.0%	38.9%
2nd derivative 4000–7500 cm^{-1}	61.1%	11.1%	27.8%	-
Mean of transversal section				
Raw 4000–10000 cm^{-1}	22.2%	-	33.3%	44.4%
2nd derivative 4000–10000 cm^{-1}	61.1%	-	38.9%	-
Raw 4000–7500 cm^{-1}	55.6%	-	50.0%	44.4%
2nd derivative 4000–7500 cm^{-1}	61.1%	11.1%	27.8%	-
Mean of longitudinal sections				
Raw 4000–10000 cm^{-1}	11.1%	16.7%	38.9%	33.3%
2nd derivative 4000–10000 cm^{-1}	55.6%	-	44.4%	-
Raw 4000–7500 cm^{-1}	11.1%	16.7%	50.0%	22.2%
2nd derivative 4000–7500 cm^{-1}	55.6%	11.1%	33.3%	-

Table 4 Best results by species for principal component analysis-linear discriminant analysis (PCA-LDA) classification of tauari samples collected in municipalities of Pará state

Species	n	Spectra	Section	Classification
Couratari stellata	6	Raw data all spectra and 4000–7500 cm^{-1}	Mean of sample	50%
Couratari oblongifolia	7	Raw data 4000–7500 cm^{-1}	Longitudinal sections	57%
Couratari guianensis	4	2nd derivative 4000–7500 cm^{-1}	All sections	100%

characteristics in spectra obtained from solid material (Muñiz et al. 2016, Nisgoski et al. 2018b).

For native species, a database reflecting the most prevalent variations in samples' characteristics is necessary, such as age, origin and position in tree. This is the first study using NIR spectroscopy on wood marketed as tauari, and the exploratory results showed the possibility of application in practice. However, analysis of more species of the *C.* genus and Lecythidaceae family is recommended.

CONCLUSION

The NIR spectroscopy, based on principal component analysis of second-derivative spectra showed promising results for characterisation and identification of species from the tauari group. The PCA-LDA, with data in the region of 4000–7500 cm^{-1}, provided the best information for species distinction. However, further research is necessary to build a database with maximum diversity of species from the *C.* genus and others genera and species of the Lecythidaceae family that are similar, using samples grown in other edaphoclimatic conditions and from different axial and radial positions of the trees.

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