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VARIABILITY OF THE APPARENT DENSITY IN THE WOOD OF *SWIETENIA MACROPHYLLA* AND *CEDRELA ODORATA* IN THE AMAZON REGION OF PERU

LEIF PORTAL
NATIONAL UNIVERSITY ORIBIO RODRÍGUEZ DE MENDOZA DE AMAZONAS
PERÚ

MARIO TOMAZELLO
UNIVERSITY OF SÃO PAULO
BRASIL

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ABSTRACT

This study examines the radial variability of apparent wood density in two tropical commercial species, *Swietenia macrophylla* (mahogany) and *Cedrela odorata* (cedar), in the Peruvian Amazon. The hypothesis states that both species will present different radial variation patterns in wood density, with *C. odorata* showing greater heterogeneity due to its older age and the presence of mineral inclusions. Advanced methods, including X-ray microdensitometry and visual analysis with QGIS, were used to obtain radial density profiles. Results showed that *C. odorata* exhibited higher variability and a wider density range than *S. macrophylla*, mainly attributed to age and mineral inclusions affecting density measurements. These differences are important for the timber industry, influencing mechanical properties and material selection. The findings emphasize the significance of density variability for sustainable management and improving timber quality in the Amazon region.

KEYWORDS: Tropical forests, wood quality, X-ray densitometry, CITES species, wood technology.

INTRODUCTION

Wood density is a fundamental biophysical property that directly affects the mechanical, physical, and technological characteristics of tree species. Its variability, both radial and longitudinal, is due to a number of factors, including genetics, the growth environment, tree age, and its internal anatomy (Hietz et al. 2013; Vansteenkiste et al. 2007). In general, wood density is crucial for the classification and use of wood in various industries, as it influences its strength, durability, workability, and carbon storage capacity. Additionally, wood density is a key parameter for evaluating the structural properties of a tree, and it directly correlates with factors like strength, durability, and workability, all of which are critical for industrial applications (Romero et al. 2020).

In tropical forests, such as those in the Amazon region, tree species show great diversity in terms of structure and physical properties, making it even more relevant to study the variability of these properties in the context of a complex and diverse ecosystem. However, there is a lack of detailed studies on the radial variations of wood density in commercial species of the Amazon, limiting the understanding of how these variations affect the physical and technological properties of the wood. The application of advanced techniques, such as X-ray microdensitometry and QGIS software, has provided high-resolution radial density profiles, enabling a more detailed analysis of wood variability in commercially important tropical species, which is essential for understanding material properties in industrial contexts. Specifically, species like *Swietenia macrophylla* (mahogany) and *Cedrela odorata* (cedar) are recognized for their economic value, but also for their vulnerability to overexploitation, highlighting the need for studies that support their sustainable management and rational use (Cochrane 2015; Hernandez et al. 2022).

This study focuses on the radial variation of the apparent wood density in *Swietenia macrophylla* and *Cedrela odorata* in the Madre de Dios region, in southeastern Peru. The main motivation for this work lies in the need to understand how the structural characteristics of the wood vary with radial position in the trunk and the factors that may directly influence the use of these species in the timber industry. The application of X-ray microdensitometry and the analysis of radiographic images using QGIS will provide a detailed view of the wood density and its distribution along the trunk. The main objective is to determine the radial variability of the apparent wood density in *Swietenia macrophylla* (mahogany) and *Cedrela odorata* (cedar) in the Amazon region of Peru. The hypothesis is that both species will present different radial variation patterns in wood density, with *C. odorata* showing greater heterogeneity due to its older age and the presence of mineral inclusions. This hypothesis will be tested through statistical analyses that include non-parametric tests for comparison between the species, as well as a descriptive and visual analysis of the density profiles.

MATERIAL AND METHODS

Study area

The study area is located in the Amazon region of the Madre de Dios department in southeastern Peru, an area characterized by its high biodiversity and globally recognized as a biodiversity hotspot (Asner et al. 2012; Myers et al. 2000). The department of Madre de Dios covers an approximate area of 85,000 km², making it one of the most biodiverse and ecologically important regions in Peru. The samples were collected from the forest management concession of Corporación Forestal Tres Fronteras S.R.L. (CORFOREST S.R.L.), located in the Tahuamanu province, at an altitude of 332 m above sea level and at coordinates -11°31'63'' S and -69°62'38'' W. The climate of this region is tropical seasonal, with an average annual temperature of 25°C and an average annual rainfall of 2000 mm (Zepner et al. 2021). The region experiences a rainy season from November to May, followed by a dry period from June to August, which defines a key ecological context for studying the properties of local tree species that grow in a warm and humid environment. This type of climate favors high vegetation productivity and is ideal for studying the structural and physical variability of tropical tree species such as *Swietenia macrophylla* and *Cedrela odorata*, the species of interest in this study.

The choice of this site is particularly relevant as the Madre de Dios department constitutes an excellent representation of the Amazonian tropical rainforest, making it an appropriate "model" for analyzing variations in the physical properties of wood in tropical species. Additionally, this area has been the subject of multiple studies related to biodiversity and sustainable forest management, providing context for the results obtained in an ecologically significant region (Fisher et al. 2018; Martínez-Sovero et al. 2023). The presence of established infrastructure for research and forest management based on the Forest and Wildlife Law and FSC certification of several forest concessions in the department ensures the availability of complementary data and the possibility of continued monitoring of the selected species in the future.

Species selection

Swietenia macrophylla and *Cedrela odorata*, from the Meliaceae family, were selected as models for this study due to their ecological, economic relevance, and conservation status. Both species are emblematic components of the tropical rainforest of Latin America and are listed in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES 2020), indicating that their trade is regulated to prevent overexploitation. This conservation status highlights the need for scientific knowledge that contributes to their sustainable use (Cochrane 2015; Hernandez et al. 2022), especially regarding their technological and anatomical properties.

For this study, eight trees of *S. macrophylla* and nine trees of *C. odorata* were selected. The average diameters at breast height were 92 cm for *S. macrophylla* and 63 cm for *C. odorata*. Samples were collected from the base of the trees, where a wood slice was extracted from each tree. Two samples were then taken from each wood slice, with each sample being obtained from the bark towards the pith, at an approximate length of 150 mm from the bark. The commercial height of the trees was 20 meters for Swietenia macrophylla and 18 m for *C. odorata*. Regarding the age of the trees, a previous study conducted on these same wood slices determined that the average age of *C. odorata* was 178 years, while the average age of Swietenia macrophylla was 136 years. These age data have not yet been published.

Despite their commercial importance in the timber industry, there is a lack of specialized studies on the wood technology of these species, particularly in the context of South American tropical forests (He et al. 2019; Kunze et al. 2024). The selection of these two species also aligns with the general goal of the study to understand how the apparent wood density of ecologically and economically relevant tropical species varies. The comparison between *S. macrophylla* and *C. odorata* also allows for the exploration of different internal wood variation patterns due to factors such as wood anatomy, contributing to a broader understanding of the biophysical determinants of wood quality in threatened species.

Apparent wood density by X-ray densitometry

To determine the radial profile of the apparent wood density in *Swietenia macrophylla* and *Cedrela odorata*, samples of 2 cm width and 2 cm thickness were extracted from two sub-samples per tree, in a bark-to-pith direction. The samples were fixed in wooden supports and then cut transversely using a double circular saw, with an approximate thickness of 1.2 to 1.8 mm. The samples were conditioned in a Memmert climatic chamber at a temperature of 20°C and 60% relative humidity, where they were kept until they reached a stable moisture content of 12%. Subsequently, the samples were scanned using a Faxitron MX20-DC12 device in the irradiation chamber, under conditions of 5.9 kV and 33 s of exposure. A cellulose acetate calibration wedge was used to adjust and calibrate the obtained images (Cahuana et al. 2023; Portal-Cahuana et al. 2025).

The radiographic images obtained, with a resolution of 513 dpi and saved in .tif format, were processed using the RStudio software, in which the xRing package (Campelo et al. 2019) was used to extract the apparent density profiles from the wood cross-sections. The resolution used for the analysis was 0.025 mm. This methodology allowed for an accurate evaluation of the apparent density variability in the two species studied, providing a detailed radial profile for each of the wood samples of *S. macrophylla* and *C. odorata*.

Visual classification of apparent wood density using QGIS

For the visual classification of density in the wood samples, the open-source QGIS software version 3.26 (Portal et al. 2024) was used. This process consisted of several sequential steps that allowed for the visualization and analysis of density variation based on the X-ray images obtained. As a first step, a raster layer was added to the QGIS project, consisting of the X-ray image obtained from the wood samples. This image was loaded into the project and properly positioned for analysis. Next, the raster menu was accessed, and the "Calculate Raster" option was selected. The equation generated from the stepped cellulose acetate wedge, with known density, was applied along with the eight defined thicknesses. The equation used was $y = 0.2518x - 0.2347$, which was applied to obtain the density values in the wood samples. The output layer was appropriately named for further analysis. Once the density layer was calculated, the created layer was selected, and in the layer properties, the rendering type was adjusted to singleband pseudocolor. This allowed for the representation of density variations through a color scale. To improve visualization, a custom color ramp was chosen to facilitate the identification of density variations in the wood. Finally, after adjusting the density visualization, the changes were saved. The processed image, with visually represented density variations in the sample, was exported at a resolution of 1000 dpi for detailed analysis and storage.

Statistical analysis

For the analysis of the data obtained through microdensitometry, the xRing package (Campelo et al. 2019) was used, which allowed for the calculation of microdensity values for the species *Swietenia macrophylla* and *Cedrela odorata*. A descriptive analysis of the data was then performed, including the calculation of measures of central tendency and dispersion.

Since the data did not meet the assumptions of normality, the non-parametric Mann-Whitney test was applied to compare the densities of the two species. This test was selected due to its ability to evaluate differences between two independent groups when the data do not follow a normal distribution. All statistical analyses were conducted using R software, version 4.4.3 (R Core Team 2025).

RESULTS AND DISCUSSION

Descriptive analysis

A descriptive analysis of the apparent density was conducted for two tree species: *Swietenia macrophylla* and *Cedrela odorata*. The results obtained are presented below.

For *S. macrophylla*, the apparent density had a mean of 0.72 g/cm³ and a median of 0.71 g/cm³, indicating a central distribution of values that are fairly close between both measures. The standard deviation was 0.12 g/cm³, suggesting some dispersion in the data, though not excessive. The range of apparent density in this species varied between a minimum value of 0.27 g/cm³ and a maximum of 1.24 g/cm³, with a total range of 0.97 g/cm³. The distribution quantiles also showed a notable concentration of data around the median.

For *C. odorata*, the apparent density showed a mean of 0.79 g/cm³, slightly higher than that of *S. macrophylla*, with a median of 0.78 g/cm³. The standard deviation was higher in this species, reaching 0.15 g/cm³, indicating greater variability in the measurements compared to the previous species. The apparent density range was wider (Fig. 1), varying from a minimum of 0.01 g/cm³ to a maximum of 2.04 g/cm³, with a total range of 2.03 g/cm³. The quantiles of *C. odorata* also reflected a more dispersed data distribution compared to *S. macrophylla*.

From these results, it can be observed that both species have relatively high apparent density. However, *C. odorata* shows greater variability in its measurements. The difference in mean densities may be relevant when considering their practical applications, as apparent density is an important factor in the strength and use of wood.

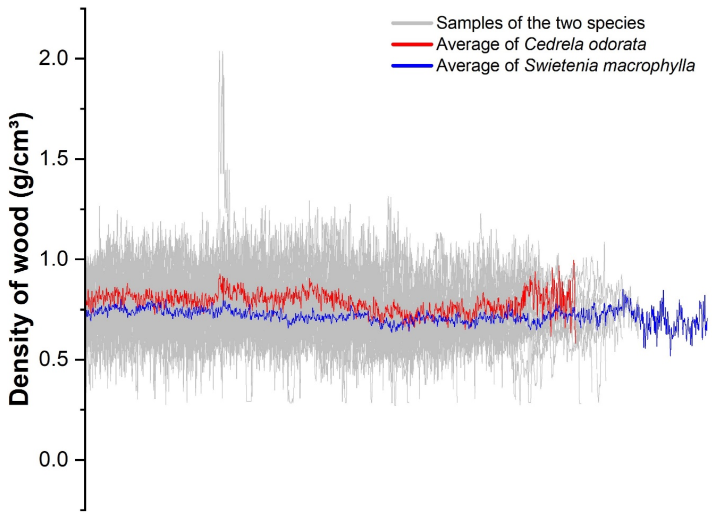

Fig. 1: Apparent wood density profile of Swietenia macrophylla and Cedrela odorata: Comparison between averages and variability. Gray lines represent the samples of both species. Colored lines represent the averages of each species. Bark-to-pith orientation.

The mean density of *C. odorata* was slightly higher than that of *S. macrophylla* (0.79 g/cm³ vs. 0.72 g/cm³), highlighting greater heterogeneity in the physical characteristics of *C. odorata* wood. This finding contrasts with expectations, as *S. macrophylla*, known for its higher mechanical strength and commercial value, would typically be expected to have a higher density than *C. odorata*. However, a more detailed analysis revealed that *C. odorata* showed concentrations of inorganic mineral inclusions, which may have increased its apparent density. These mineral inclusions, found mainly in the latewood, have a high X-ray attenuation coefficient, which can lead to overestimation of density when using microdensitometry, as suggested in previous studies such as Vansteenkiste et al. (2007).

This aligns with findings by Mo et al. (2024), who emphasized how spatial variation in wood density is influenced by environmental factors, including temperature and soil moisture, which could also affect the physical properties of wood in *C. odorata*. Similarly, Sullivan et al. (2025) discussed how wood density, as a key carbon storage indicator, varies in tropical forests and influences carbon investment strategies, highlighting its importance for forest biomass and density measurements.

Inferential analysis: Test of differences between species

To assess the difference in densities between the two species, *Swietenia macrophylla* and *Cedrela odorata*, the non-parametric Mann-Whitney test was conducted, as the data did not meet the normality assumptions according to the results of the Shapiro-Wilk test. The results of the Mann-Whitney test yielded a W value of 2,525,601,948 and a p-value < 2.2e-16, indicating a statistically significant difference between the densities of both species. These results may have relevant implications for their technological characteristics and potential use based on the physical properties of the wood.

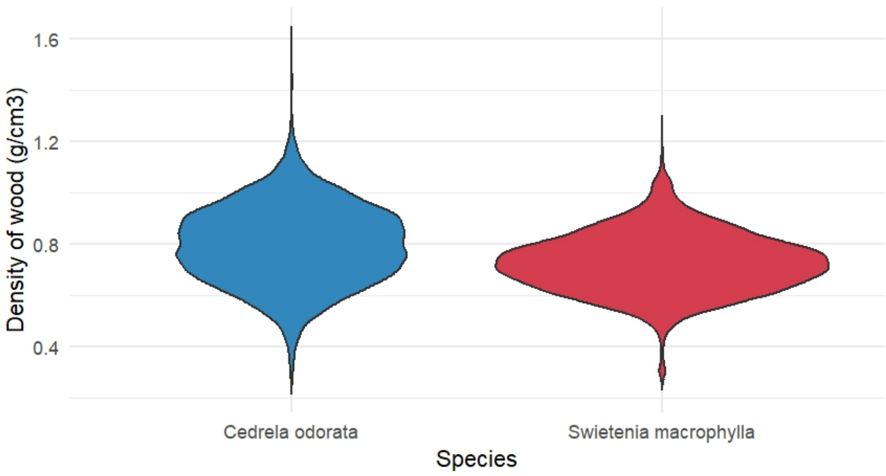

Fig. 2: Distribution of the apparent wood density of Cedrela odorata and Swietenia macrophylla using a violin plot.

The violin plot shown in Fig. 2 illustrates the distributions of apparent density for *C. odorata* and *S. macrophylla*. It can be observed that both species exhibit a bimodal density distribution, although with notable differences in the shape and extent of these distributions. *C. odorata* (in blue) shows greater dispersion in apparent density, with values ranging from 0.4 to 1.6 g/cm³, reflecting higher variability in the data. On the other hand, *S. macrophylla* (in red) presents a more concentrated distribution around its mean, with values primarily clustered between 0.5 and 1.3 g/cm³. This pattern suggests that *C. odorata* has greater diversity in the density of its wood, whereas *S. macrophylla* shows more homogeneity in its physical characteristics. These differences in density distribution could have practical implications for the mechanical properties and use of the wood from both species.

Furthermore, the fact that the *C. odorata* samples were considerably older (178 years according to classical dendrochronological techniques) than those of *S. macrophylla* (136 years) may have influenced these variations. The older age of *C. odorata* may be related to a more pronounced heartwood formation process, a phenomenon also associated with increased density in other studies. As noted by Romero et al. (2020) and Vansteenkiste et al. (2007), mineral deposits in wood increase with tree age, especially in the heartwood zones, which could partially explain the higher density observed in *C. odorata*.

The descriptive analysis showed that *C. odorata* presents greater variability in density, which aligns with previous studies documenting that some tree species exhibit more heterogeneous density distribution across their cross-section. Research by Calvo et al. (2006) and Omonte and Valenzuela (2011) has found that wood density varies along the trunk, with higher values near the periphery (bark) and lower values near the pith. This pattern was also observed in our samples of *S. macrophylla* and *C. odorata*, where the density shows a clear radial gradient, though with differences in the magnitude and distribution of those values. The wood of *C. odorata*, in particular, showed greater dispersion in density values, which may be related to a higher structural heterogeneity in this species.

These findings are consistent with the work of Cruz et al. (2019) and Hietz et al. (2013), who also highlighted the influence of radial variability on the physical properties of wood, especially in tropical species. Radial variation in density was evident in both cases, with different behaviors between the species. *C. odorata* showed considerable radial variability in density, a finding that aligns with previous studies such as Cahuana et al. (2023) and Portal-Cahuana et al. (2025), who reported that some tropical species, especially the older ones, may present variable density behavior influenced by internal anatomy and environmental conditions throughout their life cycle.

Visual analysis of apparent density in QGIS

A visual classification of the apparent density in samples of *Swietenia macrophylla* and *Cedrela odorata* was conducted through processing X-ray images in QGIS software. Fig. 3 presents the results of this analysis, where the grayscale images (top of each subfigure) correspond to the original radiographs of the wood cross-sections. In the middle of each subfigure, the processed version is shown with the application of a pseudocolor scale, allowing the identification of density variations within each sample. Finally, the bottom of each subfigure represents the apparent density profile as a function of trunk radius.

For *Swietenia macrophylla* (Fig. 3: A1, A2, and A3), a relatively homogeneous density is observed, with smooth variations along the radius. The values range from 0.26 to 0.94 g/cm³, with a slightly increasing trend toward the extremes. For *Cedrela odorata* (Fig. 3: B1, B2, and B3), the variability is greater, with a wider density range from 0.23 to 1.70 g/cm³. In particular, in Fig. 3: B1, a pronounced peak in density can be seen, which could be associated with the presence of knots, areas of abrupt transition, or structural irregularities in the wood.

The use of pseudocolors allowed for the visualization of internal differences in density distribution, facilitating the identification of structural patterns unique to each species. Overall, the results reflect that *C. odorata* presents greater heterogeneity in apparent density compared to *S. macrophylla,* which aligns with the previous statistical analyses. The differences in apparent wood density between the two species could influence key mechanical properties, such as strength and durability, which are essential for material selection in industrial applications, including construction and furniture manufacturing.

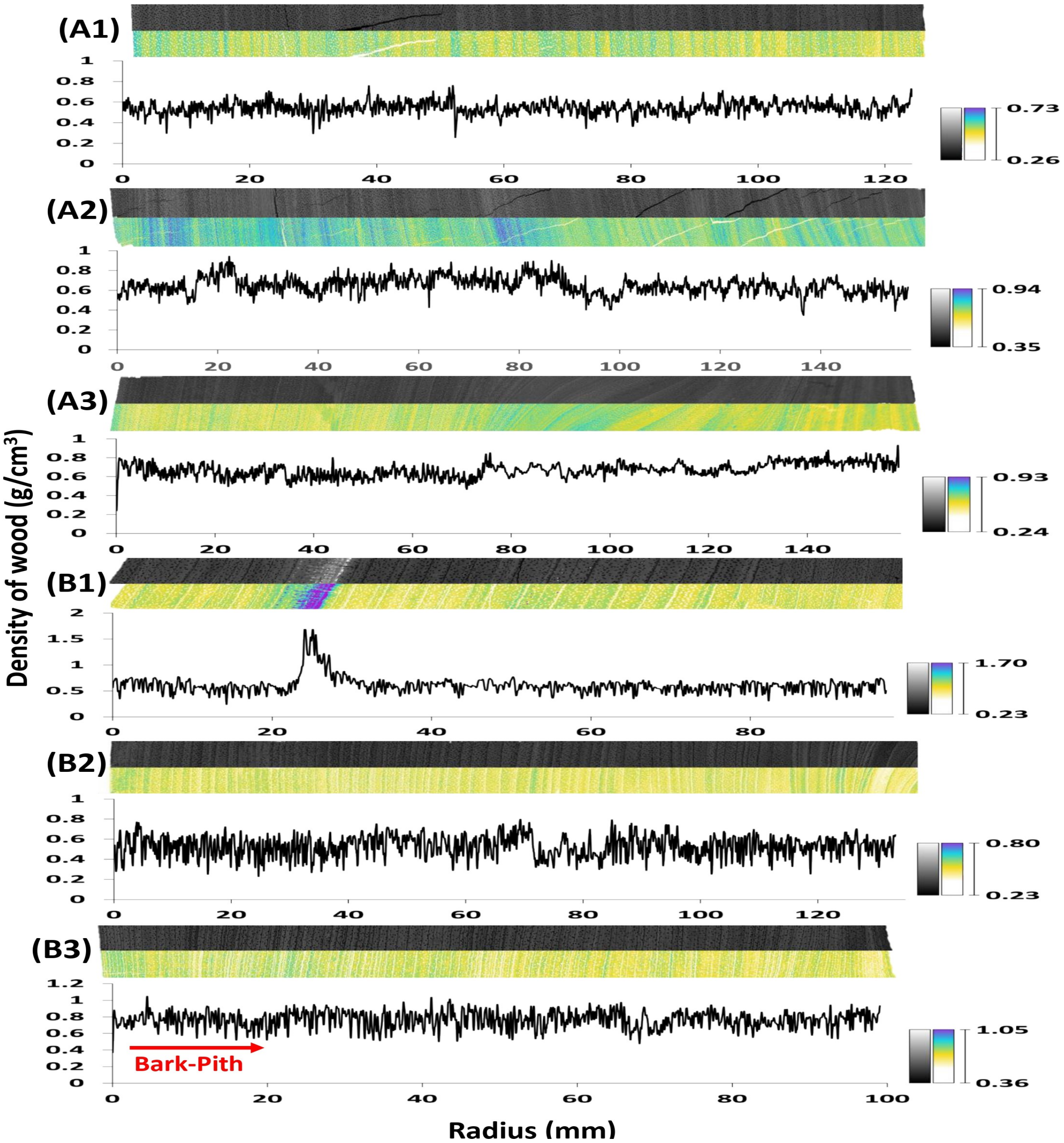

Fig. 3. Apparent density profile of Swietenia macrophylla (A1, A2, A3) and Cedrela odorata (B1, B2, B3) in cross-sections. Processed with QGIS, from bark to pith direction. In B1, at 20 mm, mineral inclusions are observed.

The visual density analysis using QGIS, with pseudocolor representations of radial variations in the X-ray images, not only supports the quantitative analysis results but also provides an innovative approach to visualizing density variation along the trunk. This method has been used in previous studies such as Portal-Cahuana et al. (2024), who demonstrated the effectiveness of QGIS in mapping radial density variation in different species. The use of pseudocolors allowed for the identification of high and low-density areas, which may be useful for future anatomical studies and for more detailed characterization of the physical properties of wood. This approach also opens new opportunities for selecting wood materials with specific characteristics, facilitating their use in industrial applications that require greater precision in wood properties.

Fig. 4 presents a visual analysis of the apparent density in wood cross-sections of *S. macrophylla* and *C. odorata*. The images processed with the pseudocolor scale in QGIS software reveal the density variations within each sample. It is observed that *S. macrophylla* wood shows a more homogeneous density distribution, whereas *C. odorata* exhibits greater heterogeneity, with clearly differentiated areas of high and low density. This visual analysis not only facilitates the identification of structural patterns but also allows for a detailed evaluation of density in the cross-sections, which could be useful for future anatomical and wood technology studies by revealing details that might go unnoticed in more conventional analyses.

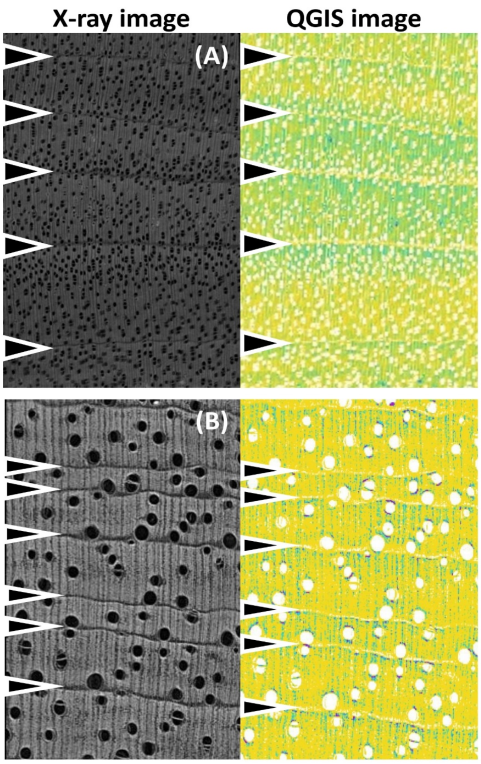

Fig. 4. Visual analysis of apparent density in cross-sections of Swietenia macrophylla (A) and Cedrela odorata (B) wood using QGIS.

Although the results obtained in this study are largely consistent with previous studies, such as Rios et al. (2018), some differences should be noted. Rios et al. (2018) found less pronounced variations in basic density in species such as *Pinus patula*, which could be explained by anatomical and growth differences between the species studied. *S. macrophylla* and *C. odorata* are tropical species with structural and biological characteristics different from those of the conifers analyzed in that study. Additionally, as noted by L. Portal-Cahuana et al. (2019), wood density variability can be influenced by environmental and genetic factors that were not fully controlled in this study, which could explain some of the observed differences.

An interesting finding in this study was the higher density observed in *C. odorata*, which, although surprising, can be partially explained by the presence of inorganic mineral inclusions, which increase the apparent density of wood, as suggested in previous studies by Vansteenkiste et al. (2007). The X-ray processed images and the density profiles obtained through QGIS showed density peaks associated with these mineral inclusions, reinforcing the idea that such deposits can significantly influence density measurement results. Moreover, *C. odorata* is an older tree compared to *S. macrophylla* (178 years versus 136 years), which could imply greater heartwood formation and, therefore, higher wood density in the inner part of the trunk, as observed in previous studies related to tree age and wood density (Romero et al. 2020).

The results of this study provide insights into material selection for the timber industry, particularly for high-value products such as furniture and construction. The observed differences in wood density between *C. odorata* and *S. macrophylla* are directly related to key mechanical properties, including strength, durability, and workability, which are critical for determining the suitability of wood for specific industrial applications. In addition, the use of technologies such as QGIS and X-ray microdensitometry to analyze radial density variation provides a powerful tool for better understanding the internal structure of wood, which can improve forest management practices. As suggested by Portal et al. (2024), this technology could help optimize the selection of wood materials for specific applications, contributing to greater efficiency in the forest industry and the sustainable use of natural resources. The results of this study underscore the significance of apparent wood density variability in the trunks of *S. macrophylla* and *C. odorata*, particularly with respect to its impact on material selection based on specific mechanical properties such as strength and durability, which are critical for industrial applications in sectors such as construction and furniture manufacturing. The density differences observed between both species could be related to factors such as tree age, the presence of mineral inclusions, and anatomical characteristics of each species. This study provides valuable insights into the factors influencing wood density variations, particularly in *S. macrophylla* and *C. odorata*. These findings contribute to a more detailed understanding of wood anatomy and its relationship with physical properties such as strength and workability, which are crucial for selecting materials for specific industrial applications.

CONCLUSIONS

This study shows that *Cedrela odorata* exhibits greater variability in apparent wood density than *Swietenia macrophylla*, with a range from 0.01 to 2.04 g/cm³ versus 0.27 to 1.24 g/cm³, and a standard deviation of 0.15 g/cm³ compared to 0.12 g/cm³. The Mann-Whitney test ($p < 2.2e-16$) confirms a significant difference. These results support the hypothesis that the greater heterogeneity in *C. odorata* is related to its older age and mineral inclusions. Advanced methods, such as X-ray microdensitometry and QGIS, provided detailed radial density profiles, enhancing understanding of wood properties and variability, crucial for sustainable management and industrial use.

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LEIF PORTAL*
UNIVERSIDAD NACIONAL TORIBIO RODRÍGUEZ DE MENDOZA DE AMAZONAS
CALLE HIGOS URCO 342, CHACHAPOYAS, AMAZONAS 01001
PERÚ
*Corresponding author: leif.portal@untrm.edu.pe

MARIO TOMAZELLO
UNIVERSIDADE DE SÃO PAULO
ESCOLA SUPERIOR DE AGRICULTURA LUIZ DE QUEIROZ
AV. PÁDUA DIAS, 11, PIRACICABA, SÃO PAULO 13418-900
BRASIL