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Wood Physics/Mechanical Properties

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Physical, vibro-mechanical and optical properties of pernambuco in relation to bow-making qualitative evaluation and wood diversity

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Abstract: Pernambuco is the archetypal wood in modern bows of the violin-family. This species (*Paubrasilia echinata*) is endangered. Existing literature suggests remaining questions on how its properties' variability relates to qualification in bow-making, and to diversity. Here 61 pernambuco specimens, with various qualitative evaluations by makers, are characterised for physical, elastic, dynamic, and optical properties. Results are compared with standard relations between-properties, and with 53 pre-selected tropical hardwoods. The tested pernambuco stands in the medium-upper range of these pre-selected species for density (ρ) and modulus of elasticity (E). It is exceptional for its very low damping coefficient ($\tan\delta$) and very intense colour (red a^*, yellow b^* and chroma C^*). Within-species variability is high. Qualification is mostly associated to ρ, colour hue angle $h°$ and gloss, then to elasticity – but E and E/ρ (specific modulus) overlap between groups. Qualification involves appearance (L^*, $h°$, gloss) when freshly cut, and with anticipation of changes after ageing or finishing. The properties (damping, chroma) that make pernambuco exceptional among species, are not clearly related to the qualification within the studied sampling. Analyses help better understand the specificities of pernambuco, and highlight the multifactorial nature of wood selection at two levels: between-species preference, and within-species qualification.

Keywords: colorimetry and gloss; diversity and variability; endangered species; mechanical and vibrational properties; musical instruments making; wood quality in craftsmanship

1 Introduction

Pernambuco wood, from the pau-brasil tree (*Paubrasilia echinata* [Lam.] Gagnon, H.C. Lima & G.P. Lewis, ex. *Caesalpinia echinata* Lam., Fabaceae–Caesalpinioideae), has, for over two centuries, been the archetypal material in making modern bows of the violin family. This species is endangered (BGCI 2022; IUCN 2022). Since the colonisation of Brazil by European, it had been intensively exploited (Bastos et al. 2022), mostly for the red dye extracted from its heartwood (Cardon 2007), until mid-19th century. Threats to this species continued through habitat loss, deforestation, urbanisation, shifts in land uses and agroindustry (Lichtenberg et al. 2022). In 2007 pernambuco was listed under Annex II of CITES. In 2022 it was proposed for Annex I (this proposal was eventually not enacted by 2022), considering that threats continued, from habitat loss and illegal trade of the wood (CITES 2023).

This situation is very complex for bow making and the cultural world of string instruments in classical music (Lichtenberg et al. 2022). Indeed, the archetypal use of pernambuco was adopted in the same time (turn of 18th to 19th centuries) as the development of the "modern" model of bows, with entangled implications of the material, of the bow structure and geometry, and of the musical repertoire, playing modes, and socio-cultural context (Ablitzer et al. 2013; Brémaud and Poidevin 2013; Lichtenberg et al. 2022). A small number of other woods are used in modern bows, but commercially this mostly concerns cheap and/or student bows (Holz 1996; Matsunaga et al. 1996). A diversity of woods has been used throughout the history of bow making, before this "modern archetype", but the socio-cultural and musical contexts were different, the geometry and structure of bows were different (Ablitzer et al. 2013), and the adopted wood materials and their properties were also different (Brémaud and Poidevin 2013).

The properties of wood for bows have been less studied than, for example, the spruce wood used for making the soundboards of string instruments (Brémaud 2012b; Carlier et al. 2018). Nevertheless, there are several important

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references on pernambuco wood properties. Sugiyama et al. (1994) and Matsunaga et al. (1996) studied wide samplings (300 and 100 specimens) for vibro-mechanical and physical (including some colorimetric) properties; and later on for the properties involved in processing and durability (Matsunaga and Minato 1998). On smaller samplings, Holz (1996) and Wegst et al. (2007) tested static and/or dynamic mechanical properties. Alves et al. (2008) and Longui et al. (2012) and Longui et al. (2010) studied anatomy, physical-mechanical properties and chemical contents. Schimleck et al. (2009) researched microstructure, extractives contents, spectroscopy, elasticity and colorimetry. Schematically, the identified characteristic features of pernambuco wood were primarily its very low viscoelastic damping (Matsunaga et al. 1996; Sugiyama et al. 1994), due to its heartwood extractives (Matsunaga et al. 1996; Minato et al. 1997), present in very high proportion (15–30 %). This has been proven by impregnating its extractives into spruce wood – which lowers its damping (Matsunaga et al. 1999). This effect depends on peculiar chemical compounds (Matsunaga et al. 2000; Minato et al. 1997, 2010), that interact with both viscoelastic and hygroscopic properties (Matsunaga et al. 2000; Obataya et al. 2001). Another characteristic of pernambuco, emerging from literature results, seems to be its high variability, as seen both within each published work, and between different publications each based on given samplings.

To understand the exclusive preference for pernambuco in high-grade modern bows, it is necessary to examine whether similarities can be found with this wood, or if it is exceptional among wood biodiversity, and for which properties. To identify which features are sought-after within pernambuco, it is necessary to examine the relations between quantitative properties and qualitative evaluations. Both are required in a quest for sustainability in bow-making materials. Quantitative and qualitative references are needed to limit the waste of material – that might also involve adaptation of geometries (Ablitzer et al. 2012; Ablitzer and Poidevin 2022; Carlsson and Tinnsten 2007), and to evaluate the wood at different positions in trunks as growth indicators (Schimleck et al. 2017) and/or from plantations (Schimleck et al. 2013), as well as potential alternatives (Holz 1996; Longui et al. 2010; Matsunaga et al. 1996; Wegst et al. 2007).

However, despite the cultural importance and sustainability challenges concerning pernambuco, there are relatively few published works comparing its material properties to the diversity of woods. On the common basis of density and elastic properties it is compared to 56 hardwood species (Sugiyama et al. 1994), nine species (Holz 1996), four species (Matsunaga et al. 1996), 13 species (Wegst et al. 2007) or six species (Longui et al. 2010). But only Matsunaga et al. (1996) base the comparison (with four species) on physical, elastic, viscoelastic, and colorimetric properties. Furthermore, only few publications (Alves et al. 2008; Schimleck et al. 2009, 2013) compare different samplings within pernambuco species, on the combined basis of quantitative properties and of a qualitative evaluation by bow-makers. From these few works, qualification involves – potentially – aspects of anatomy and extractives content, and – most likely – of density and stiffness, but with some overlapping between "qualities" (Alves et al. 2008; Schimleck et al. 2009).

Therefore, the objectives of the present study were to try to better understand: (i) where pernambuco is positioned among biodiversity of wood properties; (ii) the specificities of pernambuco; (iii) which features are appreciated in bow-making? This work wished to provide some incremental knowledge on these questions. The research was based on a sampling (61 specimens from eight batches of wood) covering different qualifications of pernambuco for bow making. A range of physical, vibro-mechanical, and optical/appearance properties were measured, using the same experimental protocol and devices as previously conducted on 53 tropical hardwoods pre-selected on the basis of their coverage of a wide range in properties and/or of their uses in woodcrafts, including instrument making (Brémaud et al. 2012, 2021). The within-species variability in properties of the studied pernambuco sampling was compared to its craftsmanship qualifications. It was analysed in the frame of between-species diversity and standard relationships between properties. Other ongoing research works, focused on deeper analyses of pernambuco's within-species variability, are going to be published in forthcoming articles.

2 Materials and methods

2.1 Wood sampling and bow-making qualification

The studied sampling of pernambuco came from eight initial batches (named P1 to P′8) of wood. Batches P1 to P6 were provided by a bow maker and ranked by "feeling of quality", noted from F1 for Batch P5 *("Really good wood, great bows made of such wood")* to F6 for Batch P3 ("*Out of curiosity, the ugliest wood to be found […], not worth a try*"). Two batches (P′7 and P′8) came from another provider and were not ranked by "feeling of quality", but were stated as "*a medium quality*" and "*a better quality*". The eight different batches were grouped into "Better", "Good", "Medium" and "Poor", from the comments of two providers of samples/workshop offcuts. The eight batches came from offcuts of instrument-making, each batch consisting of between one and six pieces of wood of various shapes, from which a total of 61 test specimens were cut (see below). After all measurements and analyses had been conducted, a sub-sampling (the 16 test specimens pictured in Figure 1b) was presented to six other bow-makers. In an absolute scale, opinions varied about the studied wood as a whole. Some makers considered the total sampling as "*a nice selection of woods for bow-making*". While some others considered this sampling included "*mostly the commonly found pernambuco, but few of the most esteemed kind*". Still, in a relative scale, the ranking of wood samples by "feelings of qualities" was very similar between makers (except for batches P6 and P′8). It must be pointed that qualification was noted as from makers' empirical experience. It was not strictly quantified by psycho-sensory experiments – hence the unformal terms "feeling of quality" and "qualification grouping". It nevertheless corresponds to a craftsmanship reality, and the comments can provide further information.

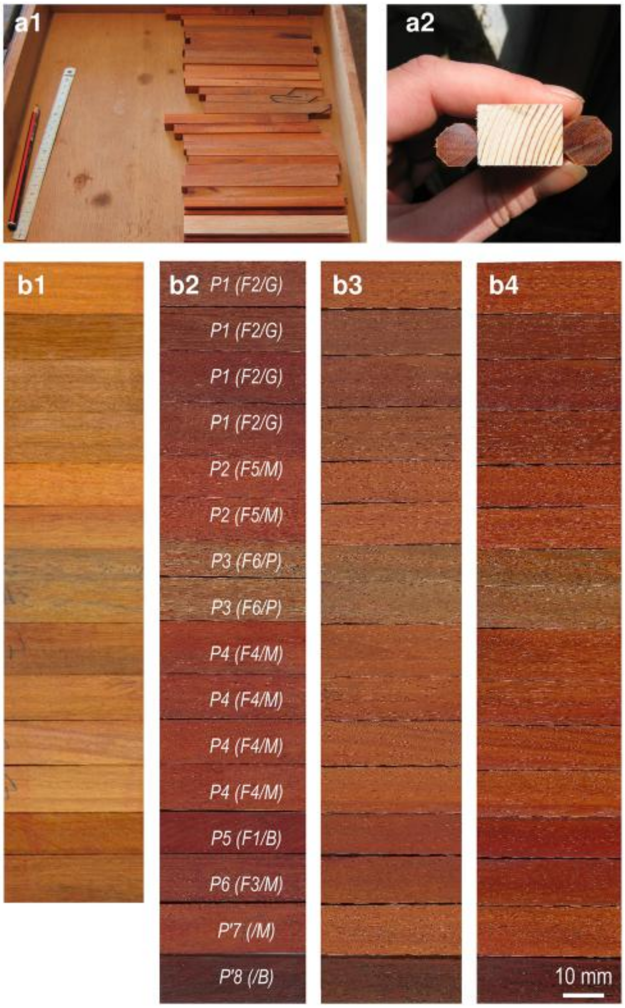


Figure 1: Studied sampling of pernambuco. (a) Specimens' preparation, (b) appearance and history. (a1) Pre-cuts from uneven-shaped bow-making offcuts; (a2) semi-finished broken bow-sticks, glued to un-used wood to allow machining (b1, b2) raw-cut (fine circular saw) surfaces (b1) freshly cut (b2) after 18 years ageing; the batch number (P1–P′8), "feeling rank" (F1–F6), and "quality grouping" (P: 'Poor', M: 'Medium', G: 'Good', B: 'Better') are indicated (b3) "refreshed" (sanded at grit #220) and (b4) polished (grit #4000) surfaces. Note: earlier images (b1) were obtained with a different optical scanner than later images (b2, b3 and b4, that were imaged with a single scanner).

2.2 Preparation of specimens

The initial wood batches were in varied, irregular geometric shapes. The material collection took place in 2004, i.e. before the CITES listing of pernambuco in Annex II, yet the wood supply was already uneven (Matsunaga et al. 1996). The highest quality wood was often in the form of "bow-blanks". In woodcrafts, the term "blanks" refers to pre-selected pieces of wood, cut as close as possible to the final dimensions of the object to be produced (here a bow stick). Therefore, bow-blanks leave nearly no spare material that could be used for laboratory test specimens. Some of the highest quality wood could however be tested from semi-finished bow sticks that had unfortunately broken (Figure 1a2). As a result, the 'Better' quality is represented by five specimens only, while the 'Good' and 'Medium' include 17 and 34 specimens, and the 'Poor' only five specimens (as bow makers would usually not store this lowest quality). In total, 61 specimens were prepared for testing. Figure 1a illustrates some steps in the preparation of specimens, that were cut to nominal dimensions of (8–)12 × 2 × 150 mm^3 (radial × tangential × longitudinal).

2.3 Conditioning and history of test specimens

Specimens were oven-dried (in order to reach stabilised "air-dry" conditions in adsorption), in mild conditions (to avoid modification of extractives), for 48 h at 60 °C. They were then conditioned for at least 5 weeks in controlled conditions of 20 ± 1 °C and 65 ± 2 % relative humidity (RH) before being measured. Indeed, vibro-mechanical properties, notably viscoelastic damping tanδ, are highly dependent, not only on equilibrium moisture content (EMC) that can be reached within approximately one week on these dimensions (Brémaud and Gril 2021a), but also on *changes* in moisture, that induce destabilisation effects over a much longer period of time (Brémaud and Gril 2021b).

All initial measurements (physical, vibro-mechanical and colorimetric) were conducted in these conditions.

Colorimetry was measured again after 18 years ageing, and Gloss was added at that step. The appearance of specimens at different steps is illustrated in Figure 1b.

2.4 Physical measurements

Mass and dimensions of specimens stabilised at 20 °C and 65 % RH were used to calculate the air-dry density ρ (kg m^{-3}), the specific modulus of elasticity (E/ρ, see below), and the EMC. After the measurements of other properties were completed, the oven-dry (at 103 °C) mass of specimens was measured to calculate EMC.

2.5 Vibro-mechanical measurements

The test principle was non-contact forced-released flexure vibrations on free-free slender beams (Obataya et al. 2000), as in several previous research works on pernambuco properties (Matsunaga et al. 1996; Minato et al. 1997; Sugiyama et al. 1994), with a custom-built hard- and soft-ware (Brémaud et al. 2012).

Specimens were hung by thin threads located at the nodes of the first mode of flexural vibrations. They were set into vibration through an electromagnet facing a thin steel plate glued onto one end. The displacement was measured by a laser triangulation displacement sensor. A wide frequency sweep detected the resonance frequency of the first mode. The specific modulus of elasticity (E/ρ) was calculated by the Euler-Bernoulli formula, from this frequency and the dimensions (Brémaud et al. 2012; Obataya et al. 2000). A second narrow frequency sweep centred on this resonance frequency measured the damping coefficient by the bandwidth method ($\tan\delta \approx 1/Q$, where Q is the "quality factor"). Then, the specimen was set into vibration at the single frequency of resonance, the excitation stopped, and the damping coefficient calculated from the decrement of vibrations' amplitude ($\tan\delta \approx \lambda/\pi$, where λ is the "logarithmic decrement"). In the range of wood, frequency- and temporal-results should be equal, i.e. $\tan\delta \approx 1/Q \approx \lambda/\pi$ (Brémaud et al. 2012).

Potential experimental errors are quantified in (Brémaud et al. 2012; Brémaud and Gril 2021a). Measurements were conducted in triplicate on each specimen. Variations between repetitions were ≤3 % for $\tan\delta$ and <<1 % for E/ρ (yet, small variations in thickness give a theoretical incertitude of <6 % on E/ρ (Brémaud et al. 2012)). For the determination of modulus of elasticity, given the very high slenderness (length/thickness ratio) of the specimens, the effect of shear and rotary inertia can be neglected, therefore values obtained by Euler-Bernoulli theory are equal to those that would have been obtained by Timoshenko theory (Brémaud et al. 2012). Values of modulus of elasticity obtained by resonance flexure methods, as used here, are nearly identical to values obtained by static four-points flexure tests (Haines et al. 1996).

2.6 Computed indexes or indicators

The "Performance Index", here noted *PI*, is proposed in the field of material selection in engineering, as an indicator of mechanical performance of materials for bows. This index ($PI = E^{1/2}/\rho$) describes the bending stiffness per unit mass of a beam or bow-stick (Wegst et al. 2007). *PI* provides a different information than E and E/ρ (Testa 2023; Wegst et al. 2007). E/ρ is primarily, in wood science, an indicator of intrinsic stiffness of wood (related to the orientation of wood elements, i.e. grain- and/or microfibril-angle), once decorrelated from the effect of density. It can be expressed by units GPa/Mg m^{-3} = $10^6\ m^2\ s^{-2}$. E/ρ is also proportional to the square of the sound propagation celerity, used in some tools for technical grading of bow-making wood (Alves et al. 2008; Fouilhé et al. 2012; Longui et al. 2012; Testa 2023; Wegst et al. 2007).

The "Deviation to Standard Damping" (or "Normalised Damping"), noted DSδ (Brémaud et al. 2009, 2012), is a statistical indicator of the difference between observed $\tan\delta$ and its values that would be predicted by the strong standard relation between $\tan\delta$ and E/ρ (Brémaud et al. 2012; Ono and Norimoto 1983). DSδ thus indicates the damping once decorrelated from the specific modulus, i.e. the part of damping not related to grain- or microfibril-angle, and usually related to the chemical composition (Brémaud et al. 2010b).

2.7 Optical measurements

Colorimetric parameters were measured with a spectrophotometer, in the specular reflexion included (SCI) mode, with CIE 10° standard observer curves, and standard Illuminant D65. Data were expressed in the CIE$L^*a^*b^*$ system, where L^* is lightness (0 = black, 100 = white), a^* is the green ($-a^*$) to red-magenta ($+a^*$) axis, b^* is the blue ($-b^*$) to yellow ($+b^*$) axis; and in the circular coordinates system CIE$L^*C^*h°$, where C^* ($C^* = \sqrt{a^{*2} + b^{*2}}$) is the chroma (i.e. distance from the grey axis, expressing "intensity" of colour), and $h°$ ($h°$ = arctan (b^*/a^*)) is the hue angle (0° = red-magenta; 90° = yellow).

Colorimetry was measured on freshly-cut surfaces, then after 18 years ageing of specimens (in ambient conditions but without direct light exposure), both with the same device (Datacolor microflash 200). At the later step, the specimens were measured again with a more recent device (Konica Minolta CM-26 d), that gave nearly equal values, and further provided visible spectra (360–740 nm) on aged and on “refreshed” (by sanding) surfaces.

Gloss, expressed as “GU” (Gloss Units), was measured with a 60° angle micro-aperture (2 × 4 mm^2) glossmeter (3 nh NHG60 M), with six points per specimen. Gloss was tested on all specimens on raw-cut (circular saw with fine blade) surfaces, then on a sub-sample of 16 after different finishing steps, defined from the advices of a bow maker: sanded with #220, #600 grit sandpaper, then #1500, #2400, and #4000 grit “Micro-Mesh® Abrasive and Polishing Cloth”.

2.8 Data analysis and comparisons to previous results

Analyses of results on pernambuco wood were done at different levels: 61 tested specimens; eight initial batches of wood; six “feelings of quality”; four “quality groupings”.

Gloss and colour changes were tested on pernambuco only. For all the other properties, results were compared with data previously obtained and published by the author on 53 selected species of tropical hardwoods. The rationale for comparison with these datasets was that they were obtained with exactly the same protocol and devices, both for physical and vibro-mechanical (Brémaud et al. 2012) and colorimetric (Brémaud et al. 2021) properties. These 53 tropical species had been initially selected for three main goals: (i) to cover a wide range in properties (in order to support trends of interrelations between properties); (ii) for testing statistical models using physico-chemical indicators to predict vibro-mechanical properties (Brémaud et al. 2010a); (iii) to characterise some of the tropical hardwoods used by high-end woodcraftspersons and specially by musical instruments makers. The material from (i) and (ii) was selected from the CIRAD databases of wood properties (Brémaud et al. 2010a; Gérard et al. 2019; Langbour et al. 2019). The material from (iii) had been provided by several French craftspersons, covering woods used for plucked- and bowed-string instruments, and, for bow-sticks specifically, tropical species used for pre-modern bows, i.e. Renaissance, Baroque and Classical (Brémaud and Poidevin 2013). The list of these 53 tropical species, with their botanical names, families, density and vibro-mechanical properties, can be found in Brémaud et al. (2012).

3 Results and discussion

3.1 Within-species variability of pernambuco, compared to between-species diversity in selected tropical hardwoods

Properties of the tested sampling of pernambuco are compared to those of 53 tropical hardwood species in Table 1.

Table 1: Pernambuco’s within-species variability compared to between-species diversity in pre-selected tropical hardwoods.

Variable	Pernambuco						Selected tropical hardwoods				
	8 batches	Statistics between 61 specimens					Statistics between average values per species (53 species)				
	Mean	Mean	SD	CV (%)	Min	Max	Mean	SD	CV (%)	Min	Max
Density ρ (kg m^{-3})	1,005	974	76	8 %	897	1,177	921	202	22 %	475	1,314
Moisture content EMC (%)	8.2	8.3	0.5	6 %	6.6	9.4	8.6	1.3	14 %	6.1	10.8
Elastic modulus E_L (GPa)	20.8	21.0	2.9	14 %	15.3	29.3	19.7	6.8	34 %	7.8	34.9
“Performance index” PI (GPa$^{1/2}$/Mg m^{-3})	4.5	4.7	0.3	5 %	4.0	5.2	4.9	0.8	17 %	3.3	6.8
Specific modulus E_L/ρ (GPa/Mg m^{-3})	20.6	21.5	2.1	10 %	16.0	28.1	21.3	4.9	23 %	9.2	29.9
Damping coefficient tanδ_L (× 1,000)	4.5	4.3	0.6	14 %	3.4	5.9	6.1	1.8	30 %	3.9	12.0
Deviation to standard damping DSδ (%)	−42	−43	6	14 %	−53	−25	−23	18	82 %	−56	18
Lightness L^*	47	49	5	10 %	35	57	43	11	26 %	24	67
Red axis a^*	24	24	3	12 %	15	29	11	5	48 %	2	25
Yellow axis b^*	31	31	5	15 %	16	37	16	8	50 %	1	30
Chroma C^*	39	39	5	14 %	22	47	19	9	46 %	2	35
Hue angle h (°)	52	52	2	4 %	44	56	51	11	21 %	17	74

Basic statistics between eight batches and between 61 specimens of pernambuco, and between average values per species on 53 selected tropical hardwoods. Presented values per sampling: mean, standard deviation (SD), coefficient of variation (CV = SD/mean), minimum (min) and maximum (max) values.

These species, pre-selected on the basis of their properties and/or of their uses in crafts and instrument making, are somewhat atypical. They tend to have a higher density (ρ), modulus of elasticity (E), and a lower damping coefficient ($\tan\delta$), than 270 tropical hardwood species in the vibrational properties' database compiled by the author (Brémaud 2012a; Brémaud et al. 2009).

Among these pre-selected tropical hardwoods, the studied material of pernambuco had a slightly higher ρ (≈1,000 vs. 920 kg m^{-3}) and E (≈21.0 vs. 19.7 GPa), but similar E/ρ (≈21.5 Gpa/Mg m^{-3}). The tested pernambuco sampling was consistent with most literature, where reported mean values are in the ranges 950–1,080 for ρ, 18.8–24.4 for E, 19.8–22.6 for E/ρ (Alves et al. 2008; Holz 1996; Matsunaga et al. 1996; Schimleck et al. 2009; Sugiyama et al. 1994; Testa 2023). The index of bending stiffness per unit mass (*PI*) of pernambuco was not higher than on compared species (≈4.7 vs. 4.9, or vs. 4.6 on species with densities 900–1,200 kg m^{-3}). Pernambuco clearly had exceptionally low values of viscoelastic damping: average value of $\tan\delta$ of 0.0043 vs. 0.0061 – that is, a highly perceptible difference for experienced instrument-makers (Hase 1987); and average DSδ of–43 %, versus –23 % for 53 selected species, and–7% for 270 tropical hardwoods (Brémaud et al. 2009). Pernambuco in average had only slightly lower equilibrium moisture content (8.3 vs. 8.6 %), but the pre-selected tropical hardwoods species had significantly lower EMC (8.6 %) than "standard" (≈10.4 % for spruce or maple in the same conditions (Brémaud and Gril 2021a)). Among the selected tropical hardwoods, which included a high proportion of "dark and reddish" woods (Brémaud et al. 2021), the colour of the freshly-cut pernambuco appeared slightly lighter, of average hue (h°), but its colour intensity was exceptionally high: two times the average values of "red" a*, of "yellow" b* and of chroma C*.

Beyond average values, the amplitude and distribution of properties deserve consideration. Within-species variability of pernambuco was high, as already noted by Sugiyama et al. (1994). In Figure 2 it is compared with the between-species diversity. In order to evaluate the dispersion of pernambuco to that of other pre-selected species,

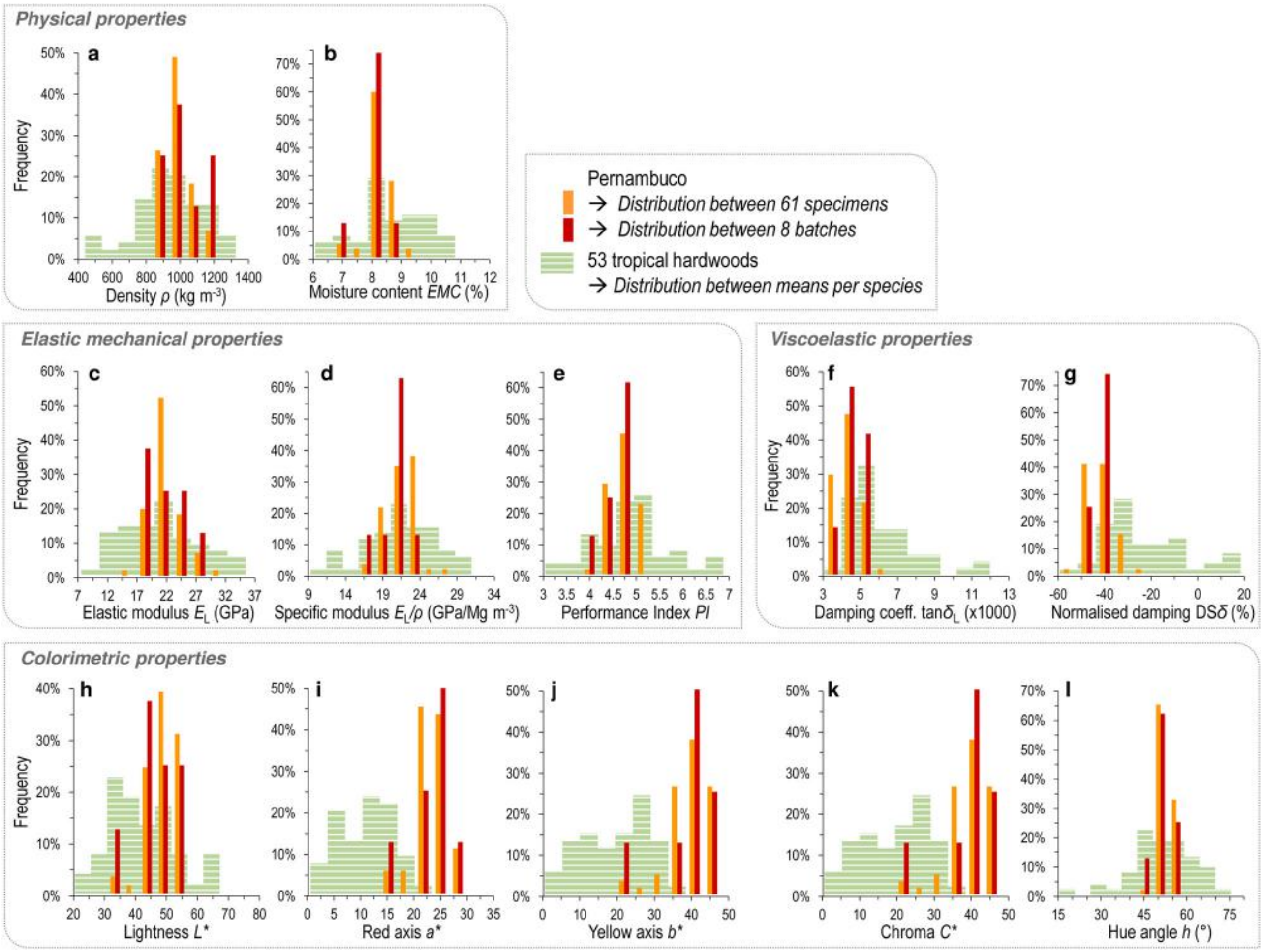


Figure 2: Histograms of all studied properties, between mean values per species (dashed green bars, 53 tropical hardwoods) and between individual values per specimens (orange bars, N = 61) or mean values per sampled batches (dark-red bars, N = 8) of pernambuco.

their respective standard deviations were compared. Some properties of pernambuco appeared relatively stable: pernambuco's hue angle $h°$, tanδ and DSδ, and *PI*, spanned only 20–35 % of the between-species variability. Its ρ and *EMC* were more variable (35–40 % of between-species variability). But its E, E/ρ and L^* were highly variable (40–45 % of between-species variability), and its colour intensity (a^*, b^* and C^*) extremely so (50–60 % of between-species variability).

Pernambuco's variability stood within the medium-to-upper ranges of other selected tropical woods for density and modulus of elasticity. Its E ranged from 16 to 29 GPa (i.e. nearly a factor × 2), but, at least in the present sampling (see discussion in Section 3.3.1), did not reach the highest values found on a few other selected tropical hardwoods. Pernambuco's variability stood in the average range of specific modulus and of "performance index" (when excluding species of density <900 kg m^{-3}), in the average-lower range of *EMC*. But its variability was small for hue angle $h°$ (in the average range) and for tanδ (that stood in the clearly lower range among diversity). For some properties, pernambuco clearly stood outside the general distributions, even seen from these atypical pre-selected species. Pernambuco was below other woods for "Normalised damping" (DSδ); and above other woods for colour intensity (a^*, b^*, and C^*).

3.2 Properties of pernambuco samples with different "feelings of quality for bow-making"

The total variability in pernambuco's properties could be divided into different initial batches of sampled wood (dark-red bar-charts in Figure 2), that came with various "feelings of quality" for bow making (Figure 3).

The properties most clearly related to qualification were ρ, the colour hue angle h, and the gloss on cut surfaces (Figure 3a, l, m). Modulus of elasticity E also showed a very clearly decreasing trend from the highest to lowest qualifications (Figure 3c). However, the batch P6 ("feeling" F3) was an outsider, with very low E: it had a good intuitive feeling ("*Quite beautiful wood, a bit tormented, but positive impression, to be tried*"), supported by its values of ρ and dark-red colour (Figure 3a, h, 1), but irregular presence of interlocked grain strongly diminished its local mechanical properties (Figure 3c, d, e, f). For this wood P6, the later-obtained opinions from other bow-makers were lower than the initial one. Surprisingly, the equilibrium moisture content EMC (Figure 3b) was also rather well related to the qualification. Reduced sensitivity to ambient humidity might be useful for having a bow that remains stable in different playing conditions; however, as EMC cannot easily be perceived by sensory means this may reveal indirect effects or correlations. Other tested properties were not ranked according to the "feeling of quality". The "Performance Index" (*PI*) for bending stiffness per unit mass, proposed as an engineering approach to material selection for bows (Wegst et al. 2007), was not related to the qualification, the "better" and "poorest" woods both having lower *PI* than intermediate qualities (Figure 3e). For damping (tanδ and DSδ, Figure 3f, g), the total variability was small within the species, and the ranges of the different batches strongly overlapped. Colour lightness L^* of fresh wood only separated upper and lower qualifications. But an interesting aspect about colour appeared (Figure 3h–l): there was a stronger relation between the "feeling of quality" and the colour values ($h°$ but also L^* and b^*) of aged wood surfaces, than of freshly-cut wood. It suggests that experienced wood craftspersons could anticipate changes in wood appearance (Brémaud et al. 2021; Carlier et al. 2015). Gloss was an important factor in discriminating the highest "feeling of quality" of pernambuco batches (Figure 3m). This property might be related to empirical expressions such as "*transparency*", "*shiny medullary rays*", perhaps also "*porosity*". Gloss is also found strongly related to visual rating of spruce tonewood by violin makers (Carlier et al. 2018).

3.3 Pernambuco compared to standard relations between properties

3.3.1 Density and vibro-mechanical properties

Compared to the "standard hardwoods" (Guitard and El Amri 1987) relation between ρ and E (Figure 4a), pernambuco showed a rather high vertical dispersion within batches – due to interlocked grain causing local variations in grain angle (Brémaud et al. 2010b). But globally, it followed very closely the standard trend, i.e., the specific modulus (E/ρ) of tested pernambuco was similar to that of "standard hardwoods", and was close between batches. ρ and E discriminated the 'Better' batch of pernambuco clearly, slightly the 'Good', but 'Medium' and 'Poor' were mixed together. The pernambuco batches of quality groupings lower or equal to 'Good' significantly overlapped with several other tropical species (mainly from families Fabaceae, Lauraceae or Moraceae). While the 'Better' quality of pernambuco was relatively isolated, although conforming to the standard trend. Some of the compared selected tropical hardwoods with $\rho \geq 1{,}100$ kg m^{-3} had either much higher E –

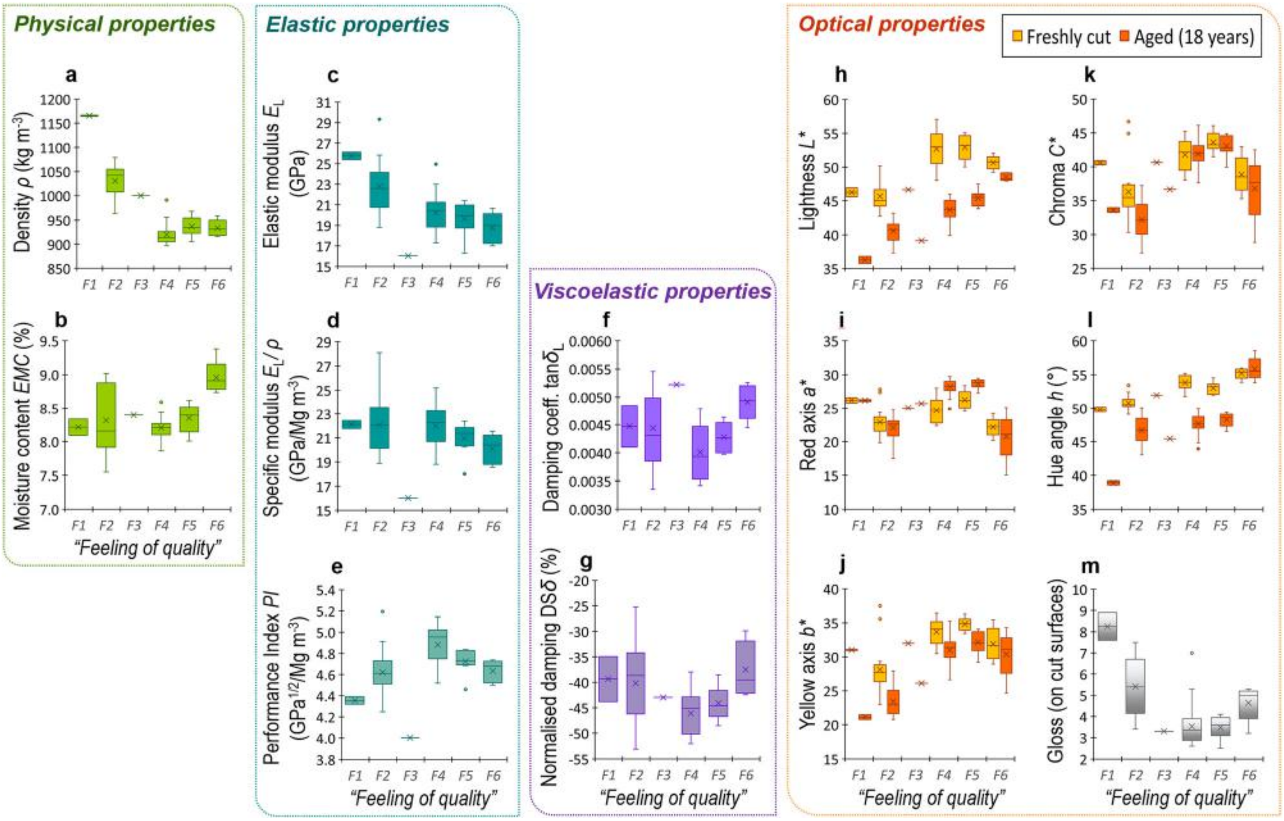


Figure 3: Box plots of all measured properties, comparing six batches of pernambuco wood with different "feelings of quality". Colorimetric properties are shown for fresh and aged surfaces.

here mainly some woods used in pre-modern bows, Baroque or Classical, such as "ironwoods" wamara and coraçao de negro (*Bocoa prouacensis*, *Swartzia panacoco* or sp.) or snakewood/amourette (*Brosimum guianense*) (Brémaud and Poidevin 2013), but also two lesser-known species that are not commercially available. Other tested woods with $\rho \geq 1{,}100\ \mathrm{kg\ m^{-3}}$ had much lower E than "predicted" by the standard trend from their values of ρ – here one ebony (*Diospyros* sp.) and two high-density true rosewoods (from *Dalbergia* genus) (Brémaud et al. 2012). As indicated earlier, pernambuco's range in ρ and E obtained in the present study is consistent with the majority of the literature (Alves et al. 2008; Holz 1996; Matsunaga et al. 1996; Schimleck et al. 2009 2017; Sugiyama et al. 1994; Testa 2023). Yet, there are occasional reports of very high values of E (30–40 GPa) in some tests on pernambuco (Wegst et al. 2007), including on historical bows (Ablitzer and Poidevin 2022). Although obtained with different methods, this might perhaps indicate different material properties for specific and/or ancient resource. The relation between growth and properties of pernambuco is very little known, yet wood from natural forest trees may have slightly higher E than plantation-trees aged 25–30 years (Schimleck et al. 2013), while no clear radial trends in ρ or E appear within three trees (*a priori* from natural forests) of pernambuco (Schimleck et al. 2017).

The damping $\tan\delta$ of studied pernambuco (Figure 4b) was related to E/ρ with the same shape as the standard trend (Brémaud et al. 2012; Ono and Norimoto 1983), a trend that expresses effects of microfibril and/or grain angle (Brémaud et al. 2010b; Obataya et al. 2000). But the pernambuco trend was strongly shifted towards very low values of $\tan\delta$. It deviated from the standard (as indicated by $\mathrm{DS}\delta$) by nearly a factor × –2. The exceptionally low $\tan\delta$ of pernambuco is known to be due to its extractives (Matsunaga et al. 1996; Minato et al. 1997; Sugiyama et al. 1994). This effect is highly related to particular extractive compounds, and would not be exactly the same, even with compounds of related chemical nature and botanical origin (Matsunaga et al. 1999, 2000). Still, on the pernambuco sampling here studied, a significant variability in $\mathrm{DS}\delta$ could be observed (from–53 % to "only" –25 %). Pernambuco partly overlapped with some other pre-selected species – here mostly belonging to the families Fabaceae and Moraceae that can exhibit abnormally low damping (Brémaud et al. 2009). But these species in the vicinity were also atypical, either known for their uses in instrument-making, and/or because the effects of their

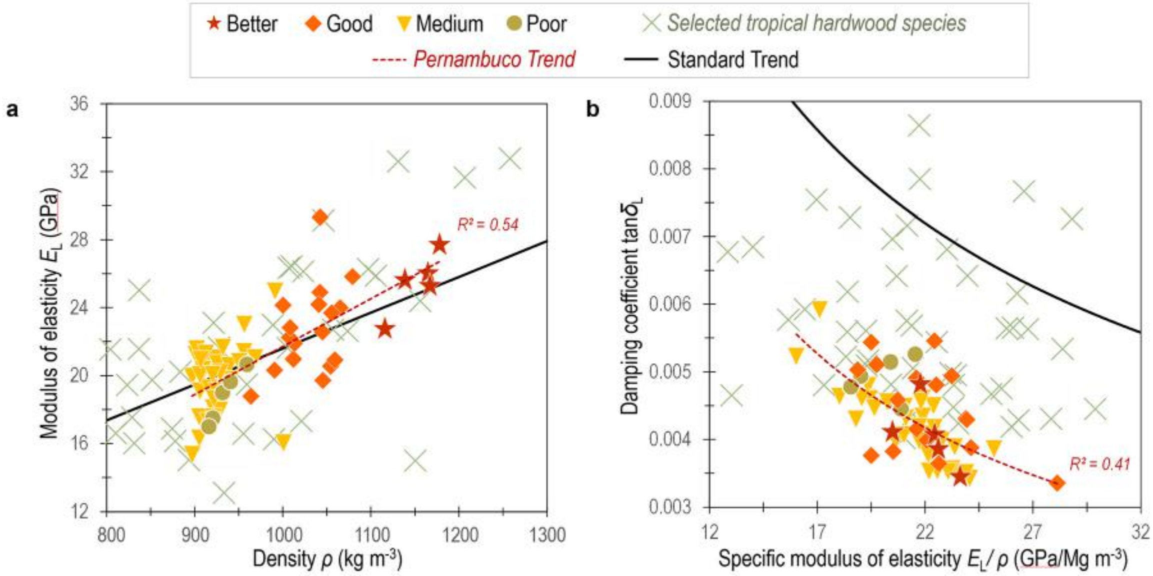


Figure 4: Comparison of results on pernambuco (closed symbols, 61 specimens, grouped by "quality") with (thick solid lines) standard relations (a) between density and modulus of elasticity (Guitard and El Amri 1987) and (b) between damping coefficient and specific modulus of elasticity (Brémaud et al. 2012; Ono and Norimoto 1983), and with selected tropical hardwoods (crosses: mean values per species); 36 species are included within the x- and *y*-axes scales shown in (a), 49 species in (b).

extractives have also been evidenced; the later were true rosewoods (*Dalbergia* spp.) (Yano et al. 1995), African padauk (*Pterocarpus soyauxii*) (Brémaud et al. 2010b, 2011) or muirapiranga/bloodwood (*Brosimum rubescens*) (Minato et al. 2010). Still, the very lowest values of tanδ observed on pernambuco stood alone, below the minimum of other pre-selected species, and appeared exceptional among wood biodiversity. Exceptionally low values of tanδ could be found in 'Better', 'Good', or 'Medium' batches. Most specimens of the 'Better' quality were in the lowest range of tanδ (≤0.004), and most of the 'Poor' in the upper range of pernambuco (≥0.0045), but the different studied batches were much more mixed in terms of tanδ and E/ρ (Figure 4b), than of E and ρ (Figure 4a).

3.3.2 Colorimetric properties

Pernambuco wood colorimetry has previously been studied for within-species correlations to properties, extractives, or qualification (Matsunaga et al. 1996; Schimleck et al. 2009). It was seldom compared to between-species diversity. In Figure 5 the studied sampling of pernambuco is compared to other selected hardwoods, and to trends (Brémaud et al. 2021; Nishino et al. 1998) between individual colorimetric parameters and lightness L^*. The "intensity" of colour must be observed in relation to L^*, as a^*, b^* and C^* increase with L^* for "dark" woods, and decrease with L^* for "light" woods (Nishino et al. 1998).

Pernambuco appeared absolutely unique regarding its very high colour intensity/chroma C^*: the vast majority of tested pernambuco specimens stood much above the trends and all other species studied by Brémaud et al. (2021) and Nishino et al. (1998). Pernambuco had particularly high values of "red" a^*, deserving its other name pau-brasil ("ember-coloured wood"), but also a majority of high values of "yellow" b^*. The only other species that comes in the vicinity is African padauk (*P. soyauxii*), with as much a^*, but less b^*. The hue angle $h°$ of pernambuco decreased with decreasing L^* (as for other woods), but was slightly below the general trend. Its hue was however not as "red" as African padauk, nor as other precious tropical hardwoods such as true rosewoods (Brémaud et al. 2021). The heartwoods of pernambuco, as of African padauk, are well-known for their uses as dyes (Cardon 2007).

3.4 Evolution of surface appearance properties – ageing and finishing

Eighteen years ageing of wood surfaces (Figure 6 a–c) went together with, for pernambuco wood in average, a significant diminution of L^* (by −7 points), but a very modest diminution of the colour intensity (C^* diminished by only −2 points in average), and, still in average, a decrease of hue angle $h°$ (−5°). However, the different quality groups responded very differently (as can also been seen in reflectance

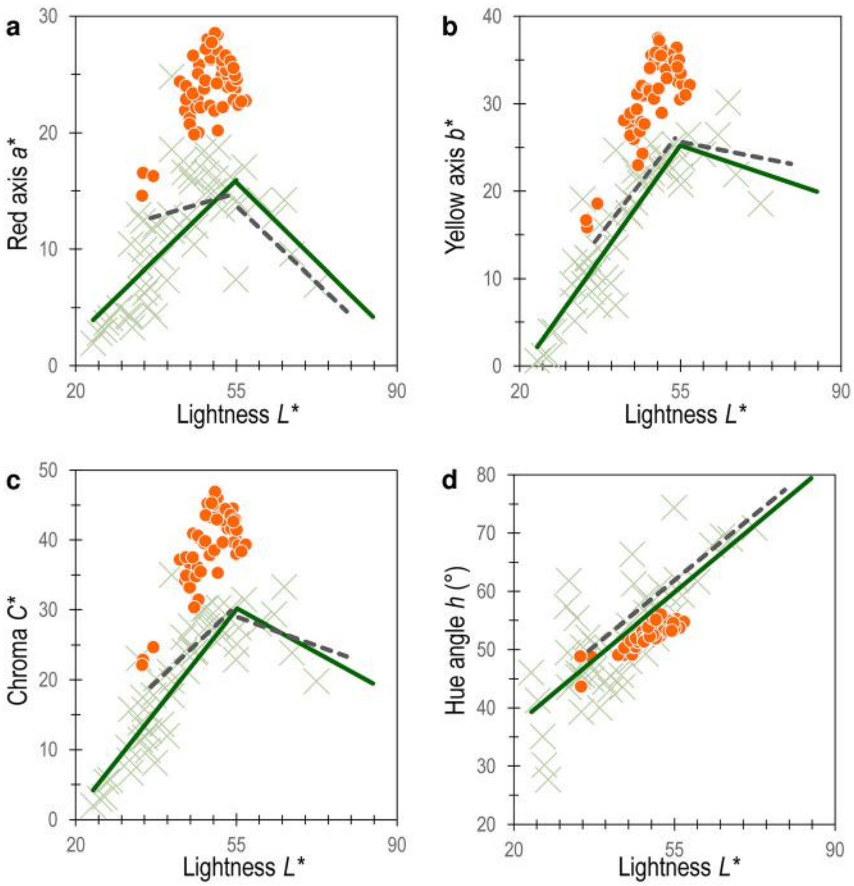


Figure 5: Relation between lightness L^* and individual colorimetric parameters: (a) "Red-magenta" axis a^*, (b) "yellow" axis b^*, (c) chroma C^* and (d) hue angle $h°$. Circles: 61 specimens of pernambuco; crosses: 53 selected tropical hardwoods (average values per species); dotted lines: trend obtained on (aged surfaces) of 98 woods from French Guiana (Nishino et al. 1998); solid lines: trend obtained on (fresh surfaces) of 98 very diverse wood types (Brémaud et al. 2021).

spectra, Figure 7). The 'Poor' darkened much less than the upper qualities. The chroma C^* decreased notably for the 'Better' and the 'Good', also slightly for the 'Poor', but was kept unchanged in average for the 'Medium'. Effects of ageing on hue angle were more contrasted: $h°$ decreased strongly in 'Better', clearly in 'Good' and 'Medium', and was slightly increased in 'Poor'. These changes were also driven by different parameters. The better the quality, the more "yellow" was lost. The global ageing in 'Better' and 'Good' was predominantly related to their strong decrease in b^* with little loss of a^*. Ageing of 'Poor' showed balanced decreases in a^* and b^*, and in 'Medium' the a^* increased while b^* decreased. This 'Medium' quality had the highest total colour difference (ΔE), and, from a light and bright-orange wood when freshly cut, became close to 'Good' after ageing. Over the whole sampling, ageing resulted in a slight contraction of the range of L^*, and in an expansion of the range of C^* and of $h°$, i.e. ageing did not reduce the colour variability within pernambuco, but rather amplified colour differences between different wood batches.

Besides ageing, another important aspect of the evolution of appearance is that of gloss, linked to the finishing processes. Yet, even on "raw" cut surfaces (by fine-tooth circular saw), the 'Better' and 'Good' batches of wood showed significantly higher gloss than the 'Medium' and 'Poor' (Figure 3m; Figure 6d). One cause can be linked to density, with denser wood getting a better cut surface, but another observation was that specimens with the lowest values of gloss on cut surfaces were those with grain deviations/interlocked grain. The 'Poor' quality batch of wood had rather little occurrence of interlocked grain, and its Gloss values were not the lowest ones.

Bow-sticks are usually finished to a very high standard of smoothness. In the present work, the evolution of gloss was studied from raw cut surface, then along progressive-grit sanding and polishing, following the technical indications of a bow-maker. As expected, the gloss dramatically increased along the whole process, with values on "rough" surfaces as low as 4 GU (="Gloss Units"), and final values as high as ≥50 GU for the finest grit studied. The lowest values were not those on the raw cut surfaces, but those with 220# grit sanding, a step that also erased any difference in gloss between wood qualities. For subsequent steps, the 'Better' batch showed slightly higher gloss than the others;

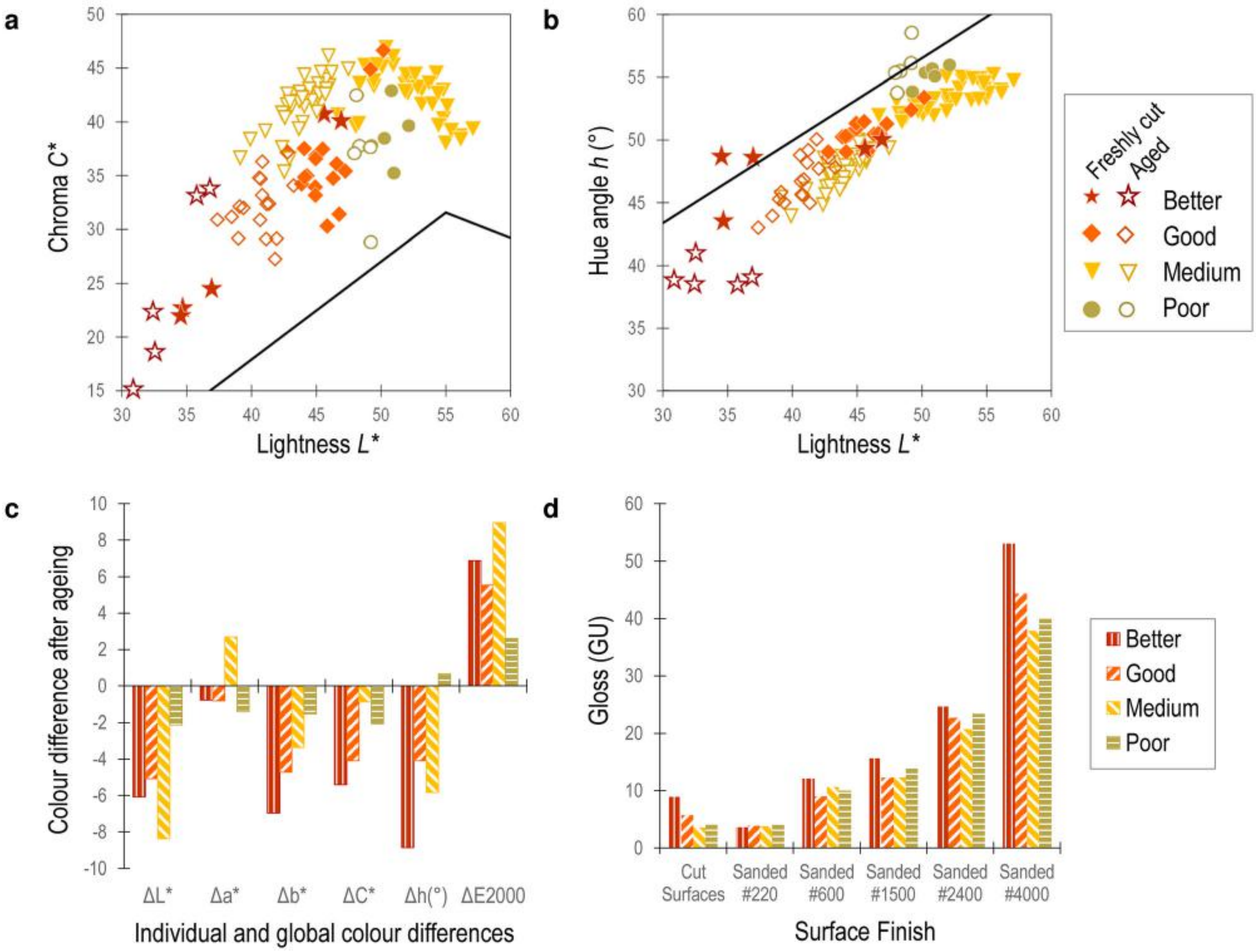


Figure 6: Evolution of appearance properties of pernambuco: (a, b, c) colour with ageing, (d) gloss with surface finishing. (a) Chroma *C** along with lightness *L**, (b) hue angle *h* (°) along with *L**, for fresh (filled symbols) and aged (open symbols) specimens grouped by "quality", and trend line on a diversity of woods (Brémaud et al. 2021). (c) Individual (Δ*L**, δ*a**, Δ*b**, Δ*C**, Δ*h*°) and global colour difference Δ*E* – CIEDE2000 (Hauptmann et al. 2011). (d) Gloss from raw cut surfaces to progressive grit sanding.

yet, sanding until the final step (4000#) was necessary before observing again a clear gradation between the 'Better', 'Good' and 'Medium' qualities of wood.

3.5 Multi-variable analyses

3.5.1 Correlations between all measured properties – pernambuco compared to selected tropical hardwoods

In order to better understand possible specificities in material features of pernambuco, its correlations between all measured properties (Figure 8, computed at the level of eight initial batches of wood) were compared to those of 52 preselected tropical hardwoods. One outlier was excluded, purpleheart (*Peltogyne venosa*) because it exhibits the single lowest value of colour hue angle $h°$ (Brémaud et al. 2021). Trends observed on these 52 selected species were consistent with those on more numerous woods (Brémaud et al. 2010a). Several trends were common to this between-species diversity and to within-species variability, but some trends differed within pernambuco. Its ρ determined a wider part (≈70 %) of the variations in E (also determined by E/ρ, i.e. by orientation of wood elements) between eight batches of wood. ρ had a much stronger (negative) correlation to colour L^* and mostly hue angle $h°$. ρ was nearly the sole descriptor of pernambuco's gloss (not measured on compared species); gloss was however also weakly related to E/ρ, that might express an effect of grain angles on surfaces. Within pernambuco, ρ was not at all associated to E/ρ nor to $\tan\delta$ (which are determined by orientation at the cell-wall- or grain-levels). E/ρ explained a much higher proportion of $\tan\delta$ within pernambuco, than it did between 52 species, and

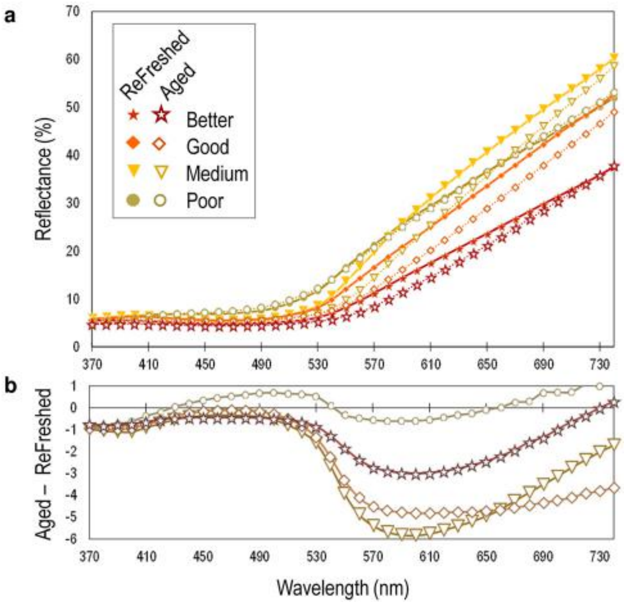


Figure 7: Reflectance spectra in visible wavelength: (a) for aged (open symbols) and "refreshed" (by sanding, filled symbols) surfaces of pernambuco, and (b) differences between aged and "refreshed" spectra.

conversely pernambuco's tanδ was less strongly explained by its DSδ. This seems logical as, within a given species, the particular chemical nature of extractives should remain relatively similar. DSδ is correlated to *EMC* between species (Brémaud et al. 2010a), and was also within pernambuco – its extractives indeed affect both its viscoelastic and hygroscopic properties (Matsunaga et al. 2000). DSδ decreases for darker and redder species (Brémaud et al. 2010a), but DSδ had no significant correlations to colour within the present sampling of pernambuco. On the contrary, pernambuco's *EMC* was very strongly linked to colour L^* and all the more so to $h°$. The relations between colour, nature and amount of extractives, and physical-mechanical properties are not straightforward. Higher extractives contents are found in darker (Matsunaga et al. 1996) and/or redder (Schimleck et al. 2009) pernambuco samples, but with very weak correlations. A trend between pernambuco's higher a^* and lower tanδ is reported by Matsunaga et al. (1996), but statistically very weak. Pernambuco heartwood always exhibits very high extractives content, from approx. 15 to 30 % (Alves et al. 2008; Matsunaga et al. 1996; Schimleck et al. 2009). Higher extractives contents are reported to be found in pernambuco samples judged as of lower quality (Alves et al. 2008; Longui et al. 2010; Schimleck et al. 2009). However, this might just reflect that exceptionally high extractives contents can increase the density without contributing much to the apparent E/ρ, thus decreasing the bending stiffness per unit mass ($PI = E^{1/2}/\rho$); yet *PI* was here not found related to "feelings of quality" (Figure 3e), nor to other properties of pernambuco (Figure 8). Correlations in Figure 8, with all properties measured on freshly cut pernambuco, were still found with aged colour, but with slightly stronger associations.

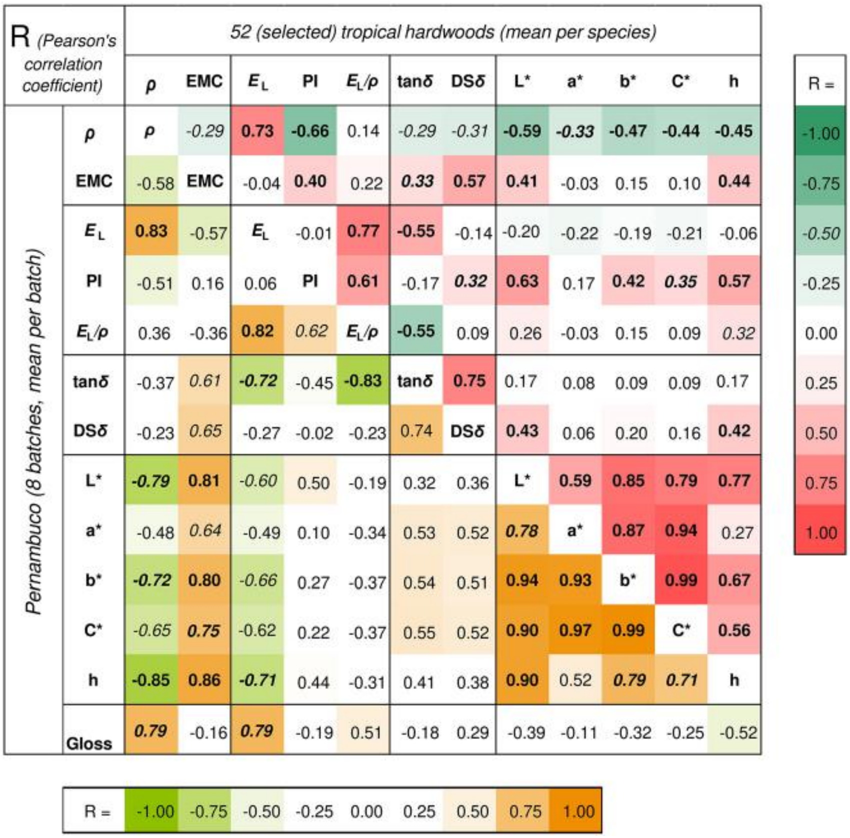
3.5.2 Principal components analysis on different "quality groupings" of pernambuco

In order to compare the different "quality groupings" of pernambuco wood based on all tested properties, a principal components analysis (PCA) was conducted. The active variables (in red in Figure 9) were selected for being as little correlated between them as possible, while representing the different types of properties. Inactive supplementary variables, quantitative (the other properties, in grey in Figure 9) and qualitative (the "quality grouping") were projected in the PCA planes. Schematically, the PCA first axis opposed (–) lighter (and yellower) woods to (+) denser, darker-redder and glossier woods; while the second axis opposed (–) more intrinsically stiff, to (+) higher damping and more hygroscopic woods.

The different "quality groupings" were more clearly discriminated between them on this multi-variable analysis, than they were by observing properties one-by-one (Figure 3) or two-by-two (Figures 4 and 6). The 'Medium' and 'Good' qualities were mostly discriminated along the first axis. The 'Poor' and 'Better' were clearly opposed along both two PCA axes.

In summary, the pernambuco wood in the 'Better' quality was a dark-red, glossy, and dense material, with damping concentrated in the lowest range. Its modulus of elasticity was high but as could be expected from its ρ. At the other end of the spectrum, the 'Poor' quality had somewhat low ρ and E, but mostly was a material with low colour intensity and "yellower", also with relatively high damping and *EMC* relative to pernambuco species. This 'Poor' group evoked a wood with unusually low content (and/or atypical nature) of heartwood extractives, and its measured properties corresponded to bow-maker appreciation ("*the ugliest wood to be found […] light, greyish, porous […], not worth to try [using it]*"). In between, the 'Medium' and 'Good' were discriminated by their density and appearance, but their physical-mechanical properties followed these primary descriptors/influencing factors.

The density and appearance properties seemed to play a strong role in the qualification of wood batches of pernambuco. Viscoelastic damping was not discriminant between qualities (except for 'Poor'), but clearly was an exceptional feature of pernambuco as a species. On the other hand,



R (Pearson's correlation coefficient)		52 (selected) tropical hardwoods (mean per species)											
		ρ	EMC	E_L	PI	E_L/ρ	tanδ	DSδ	L*	a*	b*	C*	h
Pernambuco (8 batches, mean per batch)	ρ	ρ	*-0.29*	**0.73**	**-0.66**	0.14	*-0.29*	*-0.31*	**-0.59**	***-0.33***	**-0.47**	**-0.44**	**-0.45**
	EMC	-0.58	EMC	-0.04	**0.40**	0.22	***0.33***	**0.57**	**0.41**	-0.03	0.15	0.10	**0.44**
	E_L	**0.83**	-0.57	E_L	-0.01	**0.77**	**-0.55**	-0.14	-0.20	-0.22	-0.19	-0.21	-0.06
	PI	-0.51	0.16	0.06	PI	**0.61**	-0.17	***0.32***	**0.63**	0.17	**0.42**	***0.35***	**0.57**
	E_L/ρ	0.36	-0.36	**0.82**	*0.62*	E_L/ρ	**-0.55**	0.09	0.26	-0.03	0.15	0.09	*0.32*
	tanδ	-0.37	*0.61*	***-0.72***	-0.45	**-0.83**	tanδ	**0.75**	0.17	0.08	0.09	0.09	0.17
	DSδ	-0.23	*0.65*	-0.27	-0.02	-0.23	0.74	DSδ	**0.43**	0.06	0.20	0.16	**0.42**
	L*	***-0.79***	**0.81**	*-0.60*	0.50	-0.19	0.32	0.36	L*	**0.59**	**0.85**	**0.79**	**0.77**
	a*	-0.48	*0.64*	-0.49	0.10	-0.34	0.53	0.52	***0.78***	a*	**0.87**	**0.94**	0.27
	b*	***-0.72***	**0.80**	*-0.66*	0.27	-0.37	0.54	0.51	**0.94**	**0.93**	b*	**0.99**	**0.67**
	C*	*-0.65*	***0.75***	-0.62	0.22	-0.37	0.55	0.52	**0.90**	**0.97**	**0.99**	C*	**0.56**
	h	**-0.85**	**0.86**	***-0.71***	0.44	-0.31	0.41	0.38	**0.90**	0.52	***0.79***	***0.71***	h
	Gloss	***0.79***	-0.16	***0.79***	-0.19	0.51	-0.18	0.29	-0.39	-0.11	-0.32	-0.25	-0.52

R =
-1.00
-0.75
-0.50
-0.25
0.00
0.25
0.50
0.75
1.00

R =	-1.00	-0.75	-0.50	-0.25	0.00	0.25	0.50	0.75	1.00

Figure 8: Pearson's correlation matrix between all measured properties, between 52 selected tropical hardwoods (above-diagonal), and between eight batches of pernambuco (below-diagonal). Fonts and colour scales indicate the strength of correlations (different degrees of freedom for above- and below-diagonal).

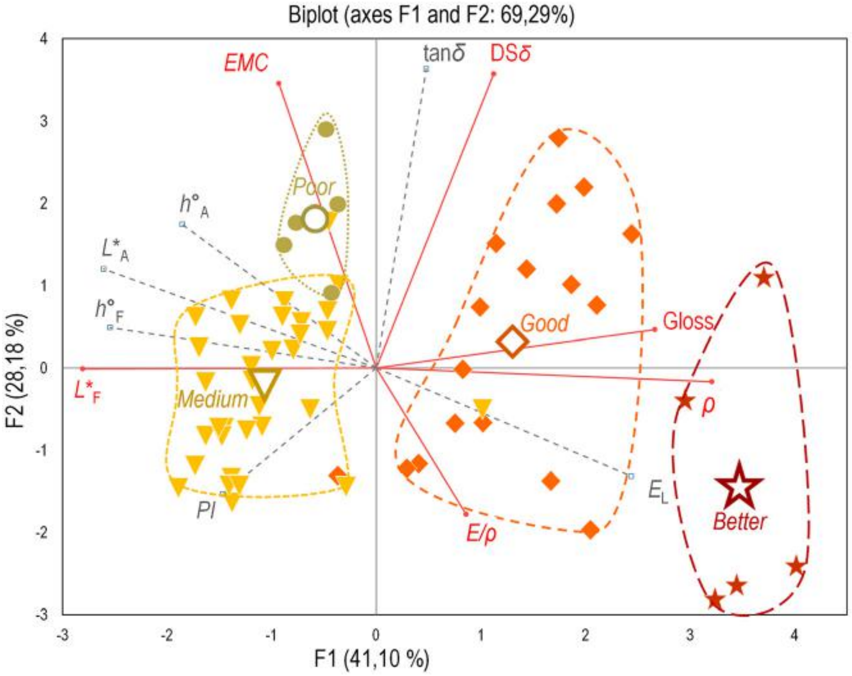


Figure 9: Principal components analysis biplot of variables (active: solid red lines; inactive: dashed grey lines) and of observations (filled symbols: 61 specimens of pernambuco; open symbols: Barycenters of four "quality groupings").

intrinsic (i.e. separated from the effect of density, E/ρ) stiffness was only weakly discriminant.

These results raise questions when considering the bow's function, that is primarily mechanical. However, the mechanical behaviour of the bow can be "tuned" through fine structural adjustments (section shape, diameter and taper; camber), as is shown in bow-mechanics (Ablitzer et al. 2012; Carlsson and Tinnsten 2007; Testa 2023), in bow-making history (Ablitzer et al. 2013; Ablitzer and Poidevin 2022; Brémaud and Poidevin 2013), and in wood science (Sugiyama et al. 1994). Exceptionally low damping of pernambuco is known (Askenfelt 1992; Matsunaga et al. 1996, 1999; Sugiyama et al. 1994), and further highlighted by the present comparisons with a diversity of pre-selected tropical hardwoods. But its role in bow behaviour is not clearly elucidated. Damping seems related to perceptual rating of bows (Askenfelt 1992), but other damping sources are superimposed to wood-material damping, through bow assembly and handling/playing (Askenfelt 1992). While $\tan\delta$ might perhaps indicate other aspects of viscoelasticity (thermal softening, creep and recovery) essential for heat-bending and maintaining over time the camber – a most important structural characteristic of modern bows (Ablitzer et al. 2012; Gough 2011; Tomezzoli et al. 2021) – this has been only preliminarily tested (Matsunaga and Minato 1998).

Appearance properties of pernambuco were, in the present study, linked both to its within-species bow-making qualification, and to its “exceptional” features among species diversity. In the literature, wood colour or anatomy are compared to bow-making qualification (Alves et al. 2008; Schimleck et al. 2009) and/or to quantitative physical-mechanical properties (Longui et al. 2010 2012; Matsunaga et al. 1996). Would pernambuco’s appearance (colour, gloss, coarseness of grain) be indicators of structure-properties relationships? In the present results, this was not clearly supported by correlation analyses (Figure 8). Yet, appearance properties represent the “first encounter” between humans and a material. Psychosensory implication of wood appearance is lesser documented in instrument-making wood, but may be an important criteria of choice *per se*, as well as a wider indicator of wood features (Carlier et al. 2018).

4 Conclusions

This work on wood properties of pernambuco, the – endangered – national tree of Brazil and the archetypal material of modern violin bows, aimed to better document how its within-species variability compares: to between-species diversity in selected tropical hardwoods, and to bow-making qualification. The main results were as follows:

- The very high variability of pernambuco wood was confirmed. But this depended on properties. Its elastic properties, and colour lightness and intensity/chroma, were highly variable, its physical properties relatively variable, but its viscoelastic damping and colour hue remained within a narrow range.
- Pernambuco was on average close to several other selected dense tropical hardwoods with regards to density and elasticity/stiffness. Yet, this was less true for the better quality samples considered.
- Pernambuco was very atypical among wood diversity for its exceptionally low damping (ascribed to peculiar extractives in the literature), and for its exceptionally high colour intensity.
- The properties that make pernambuco exceptional among species, were not necessarily those most involved in the within-species qualification. The feeling for a “better” bow-wood of pernambuco appeared to be linked to denser, redder (also darker) and glossier wood, partly only to stiffer wood; while within-species variations in damping and colour intensity were less significant.
- Appearance properties were important in the qualification. Results suggested a craftsmanship’s anticipation of changes, in colour after ageing, in gloss after finishing processes. Appearance might reveal chemistry-structure-properties relations (this was not supported by the present results but might be so in further research).
- The qualification appeared to be highly multifactorial, involving several different properties together, rather than a single or a couple of properties.

The present results provided incremental knowledge on pernambuco’s specificities among diversity, and on its appreciation for bow-making. Yet, although these results are based on a significant range of experiments and analyses, they could not alone represent a thorough, exhaustive characterisation. Several aspects of this iconic and atypical wood species would deserve future investigation: (i) better clarifying the full amplitude and the origins of its variability; (ii) studying its perceptual evaluation by bow-makers on a wider and more quantitative basis than the present exploration. Disentangling origins and implications of properties directly involved in the mechanical behaviour of the bow, of properties which role in bow behaviour is not fully elucidated, and of properties sensorially or technically prominent, will be important in the context of current challenges and sustainability issues that face bow-making wood material.

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