Research article

Use and sustainability of wood in acoustic guitars: An overview based on the global market

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ABSTRACT

Since the dawn of humanity, wood has been the material of choice for crafting musical instruments due to its favorable acoustic properties, workability, and aesthetic value. Acoustic guitars are among the most widespread musical instruments worldwide, and today are industrially manufactured by large companies with global markets. This study investigates the use of wood in modern acoustic guitars, with a focus on wood species and sustainability. The websites of the 14 most relevant manufacturers on a global scale were analyzed collecting data on 874 guitars and 4506 components. The purpose of the research is to provide a novel overview of the variety and relevance of woods employed in the sector, of the most common environmental issues associated with their use, and of the strategies adopted by companies to deal with sustainability concerns and to communicate their environmental commitment to the public.

The results show that, overall, wood remains the material of choice for acoustic guitars, and a wide number of wood species are used. Sustainability aspects are often highlighted on websites. However, the taxonomy is ambiguous in several cases, and some endangered wood species are used with limited information about preservation. Therefore enhancing the research of alternative wood species and increasing the efforts on environmental commitment and on promoting end consumer sustainability awareness are relevant targets to further enhance the use of wood in a sector that already provides a great valorization of this renewable material.

1. Introduction

Over the millennia, wood has always been a fundamental material for the construction of musical instruments. While the oldest instruments known are flutes made of bone, dating around 35000 years ago [1], wood was likely used more than bone due to its greater workability. However, as plant tissues degrade, no wooden musical instruments dating back to the Palaeolithic period have been preserved [2,3]. An example of an ancient wooden musical instrument is the so-called bullroarer, which consists of a thin wooden slat whirled around thanks to a thin cord tied at the end. More recent than the bone flutes, it is an instrument used by ancient societies for ceremonial purposes dating back to 3000 BCE [4].

A key feature that distinguishes wood from other materials is its natural variability. Instrument-makers choose from an amazingly wide array of different woods, depending on the type of musical instruments to be made, as well as the particular component [5,6]. A

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survey conducted by the authors on the "Forest Stewardship Council (FSC) Certificates Public Dashboard" (a database that collects available FSC-certified wood species for different product categories) revealed a total of 142 different wood species available in the category "W14 Musical Instruments" [7].

Besides its aesthetic value and workability, wood's acoustic qualities make it an invaluable material for musical instruments [8]. Since acoustic properties are determined by physic-mechanical characteristics, several studies focus on exploring indices and parameters (e.g. density and Young's modulus) that influence the acoustic response of wood by determining the speed and intensity of the sound [9–13].

Wood is the most commonly used material in the guitar, which is one of the most widespread instruments worldwide [5]. lists a staggering number of 309 different wood species employed in the construction of guitars, most of which are hardwoods, except for the production of soundboards. This list comprehends several species that have a long history of being used to make guitars. However, many species are now becoming less and less available, commonly because of sustainability issues. Notable examples are *Swietenia macrophylla*, known as Honduran mahogany [14], and *Dalbergia nigra*, the Brazilian rosewood [15]. The decline of these species due to illegal trade and overexploitation led to their inclusion in the Appendices of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) [16].

In many cases, manufacturers have started to adjust their production and supply practices accordingly [17,18]. [19] suggests some structural techniques that can be used in guitar construction to standardize the vibrational response regardless of material properties, thereby eliminating the differences created by divergent wood species. In addition, substitute woods or materials such as laminated wood and hybrid fiber materials are used as effective alternative solutions [20]. Many traditional wood species have been studied to determine indices useful in selecting alternatives for guitar components [21,22], showing that the use of less common woods or alternative materials does not compromise the acoustic performance of the instrument [19,23]. A blind test experiment carried out by Ref. [24] showed that numerous professional guitarists were not able to distinguish the sound produced by guitars built with expensive and rare woods (Brazilian rosewood, Indian rosewood and South American mahogany) from that produced by guitars built with cheaper and more common ones (Walnut, Sapele and Maple). This suggests that, when selecting guitars, end users often consider the aesthetic value as much, if not more, as the acoustic properties.

Despite the abundance of literature focusing on the aforementioned topics, there is a general lack of studies exploring the actual use of wood in the musical instrument industry and how instrument-manufacturing companies communicate to the consumer the role of wood in their products. Acoustic guitars are the most popular guitars all over the world. In the United States alone, approximately 1.85 million acoustic guitars were sold in 2021, representing around 55% of all guitars sold that year [25]. The importance of acoustic guitars goes well beyond the mere manufacturing numbers, as such instruments are associated with relevant socio-cultural meanings at local and global scales [26]. In addition, acoustic guitars depend more on wood for their appeal: they depend on their wood bodies for their sound and are aesthetically dominated by wood. In contrast, electric guitars are often painted, and produce their sound either mostly or entirely through the direct relation between the vibrating string and the pickup [27]. Wood is a vessel to the electric guitar, but it is the essence of the acoustic guitar.

The present paper investigates the use of wood in modern acoustic guitars, with particular reference to sustainability. To this purpose, the websites of the world's 14 major acoustic guitar manufacturing companies were analyzed, gathering information on 874 models currently on the market at a global level. The information was collected with different aims: to conduct a census of the woods used in acoustic guitars construction and their environmental sustainability, to explore if and which substitutes are used in place of endangered woods, and to assess how companies deal with environmental aspects and how the information is conveyed to the
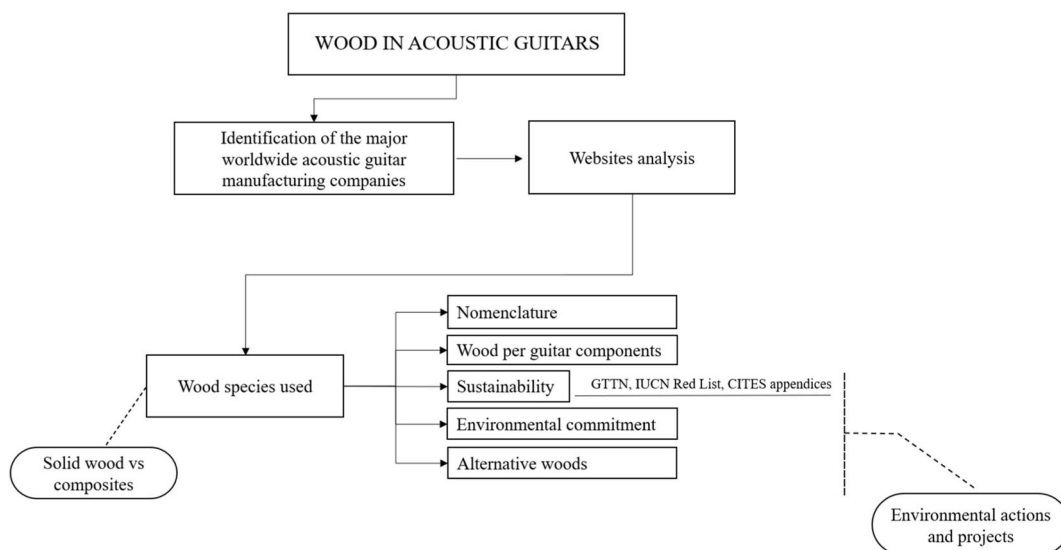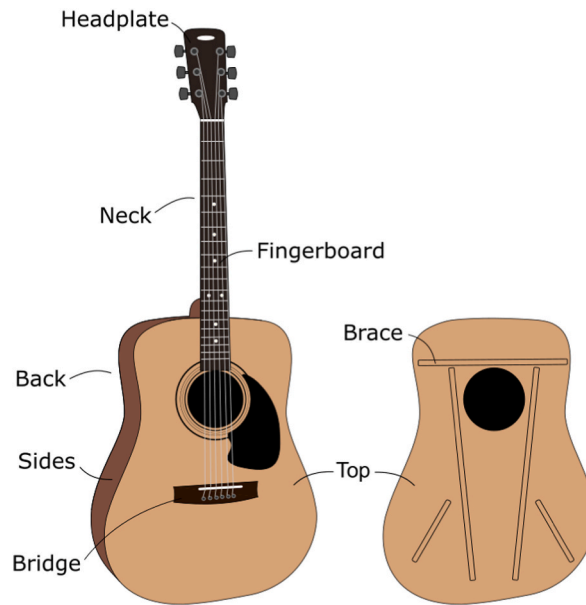

Fig. 1. Flow chart of the study.

Fig. 2. General structure of an acoustic guitar with the detail of its wood components.

customers. The outcome provides a broad overview that enables drawing some suggestions on how to improve the sustainable use of wood in acoustic guitars. Given the broadness of the sector considered, such indications can constitute a benchmark for similar questions in other sectors. A flow chart of the study is presented in Figs. 1 and 2.

2. Material and methods

To have a sizable representation of the sector we selected companies based on the data listed in Ref. [28], the market analysis report of reference for the acoustic guitar industry. We analyzed the websites of the world's 14 major acoustic guitar manufacturing companies, as website analysis is recognized as an effective method for assessing product features also in the wood sector [29]. One website was excluded that is available in Chinese only, to avoid the risk of acquiring inaccurate data due to translation issues.

All models of acoustic guitars available for sale were surveyed, for a total of 874 guitars. For each one, we recorded the wood or the other materials used in each different guitar component: top, back, sides, brace, neck, fingerboard, and headplate (Fig. 1), for a total of 4506 parts and 4616 woods (some companies reported multiple woods for a single component). When specified, the price in US$ was recorded, for a total of 558 prices.

A set of information was associated with each wood, beginning with the corresponding scientific name according to Refs. [30,31]. In fact, except for one website, only common names were found to be used. Secondly, the tropical or temperate origin was assigned according to Ref. [32]. The density, Young's modulus, and Janka hardness values were noted according to Refs. [33,34]. To assess woods' environmental sustainability, for each examined species we indicated the conservation status according to the International Union for Conservation of Nature (IUCN) red list [35], the priority level (high, medium, or low) according to Ref. [36], and the possible listing in a CITES appendix via [16]. In addition, for each wood we checked through [37] the possible availability of FSC-certified material. Finally, the occurrence of environmental sustainability projects and initiatives was assessed as well.

Descriptive statistics were calculated through Microsoft Excel (Microsoft Corp., Redmond, WA, USA). The chi-square goodness-of-fit test was performed by SPSS 28.0 (IBM Corp., Armonk, NY, USA) to verify the frequency of use for the different wood species in each guitar component, with expected uniform distribution, where significant differences were assessed through standardized residual analysis [38]. Significance was always set at a level of 0.05.

3. Results and discussion

3.1. Nomenclature

The results of the survey are summarised in Table 1. In the first column, woods are indicated by their common name as reported on the websites, while the second column reports the corresponding scientific name. In most cases, common names followed international standards such as [30,31], making the attribution of taxa straightforward. However, we encountered several instances of ambiguous nomenclature, which made the task more difficult. Nomenclature issues can be grouped into three categories, as follows.

First, different and sometimes fanciful common names were attributed to a single wood species, an example being *Picea* spp. which has been found referred to as Alpine spruce, Alpine "moon" spruce, Moonwood, Austrian red spruce, Bear claw European spruce,

Table 1
Woods employed in acoustic guitars construction.

Nomenclature			Sustainability				Guitar components[e]							
Common name	Scientific name	Product[a]	GTTN[b]	IUCN[c]	CITES	FSC[d]	Tot	T	BS	Bi	Ba	N	F	H
African Mahogany	*Khaya ivorensis*	S,P	High	VU	–	✓	0.76	–	0.22	–	–	3.56	–	–
African zebrano	*Microberlinia brazzavillenis*	S	Low	VU	–	✓	0.06	0.11	0.22	–	–	–	–	–
Agathis	*Agathis australis*	P	–	–	–	✓	0.02	0.11	–	–	–	–	–	–
Alder	*Alnus* spp.	S	–	*	–	✓	0.02	–	–	–	–	0.11	–	–
Ash	*Fraxinus* spp.	–	Low (As)	*	III (*Fraxinus mandshurica*)	✓	0.13	0.23	0.44	–	–	–	–	–
Australian blackwood	*Acacia melanoxylon*	–	–	–	–	✓	0.04	–	0.22	–	–	–	–	–
Bald cypress	*Taxodium distichum*	S	–	LC	–	✓	0.04	–	0.22	–	–	–	–	–
Basswood	*Tilia americana*	P	–	LC	–	✓	0.09	–	0.44	–	–	–	–	–
Birch	*Betula* spp.	P	Low (As, E, N)	*	–	✓	0.17	–	–	–	–	0.86	–	–
Black Limba	*Terminalia superba*	S	High	–	–	✓	0.02	–	0.11	–	–	–	–	–
Bocote	*Cordia elaeagnoides*	–	–	LC	–	✓	0.04	–	0.22	–	–	–	–	–
Dao	*Dracontomelon dao*	–	–	LC	–	✓	0.09	0.23	0.22	–	–	–	–	–
Ebony	*Diospyros* spp.	S	High (Af)	*	II (Madagascar)	✓	21.75	–	0.33	60.07	–	–	57.08	51.26
Eucalyptus	*Eucalyptus* spp.	–	Low (*Eucalyptus globulus*)	*	–	✓	0.26	–	–	–	–	–	1.39	–
Grenadillo	*Platymiscium* spp.	S	Low (*Platymiscium pleiostachyum*)	*	II (*Platymiscium parviflorum*)	✓	0.02	–	0.11	–	–	–	–	–
Indian Laurel	*Terminalia tomentosa*	S	–	–	–	–	0.71	–	0.11	2.62	–	–	1.86	–
Indian Silver Oak	*Gravillea robusta*	S	–	–	–	✓	0.02	–	0.11	–	–	–	–	–
Jatoba	*Hymenaea courbaril*	–	Medium	LC	–	✓	0.30	–	–	1.15	–	–	0.81	–
Katalox	*Swartzia cubensis*	–	–	–	–	✓	0.35	–	–	1.31	–	–	0.93	–
Koa	*Acacia koa*	S,P	–	LC	–	✓	1.04	2.05	3.17	–	–	–	–	0.36
Lacewood	*Panopsis* spp.	P	–	*	–	✓	0.06	–	0.33	–	–	–	–	–
Mahogany	*Swietenia* spp.	S,P	Low (C)	*	II	–	20.41	8.79	33.15	–	–	60.41	–	0.72
Mango	*Mangifera indica*	S,P	–	DD	–	✓	0.09	0.23	0.22	–	–	–	–	–
Maple	*Acer* spp.	S,P	High (E)	–	–	✓	2.60	0.91	5.03	0.33	–	6.69	0.23	–
Meranti	*Shorea* spp.	P	High (As)	*	–	✓	0.02	0.11	–	–	–	–	–	–
Merbau	*Intsia bijuga*	–	Medium	–	–	✓	1.71	–	–	6.38	–	–	4.64	–
Myrtlewood	*Umbellularia californica*	S	–	LC	–	✓	0.13	0.11	0.55	–	–	–	–	–
Nato	*Mora/Sapotaceae* spp.	S,P	–	–	–	✓	1.17	–	0.88	–	–	4.96	–	–
Nyatoh	*Palaquium* spp., *Payena* spp.	–	High (As)	*	–	✓	0.89	–	–	–	–	4.42	–	–
Okoume	*Aucoumea klaineana*	S	High	VU	–	✓	1.56	1.83	4.92	–	–	1.19	–	–
Ovangkol	*Guibourtia ehie*	S,P	–	LC	–	✓	2.58	0.23	1.97	7.86	–	–	5.92	–
Padouk	*Pterocarpus soyauxii*	S	High	–	–	✓	0.11	–	0.22	0.16	–	–	0.12	0.36
Pau Ferro	*Machaerium scleroxylon*	S	Medium	LC	–	✓	0.67	–	1.42	–	–	0.97	1.04	–
Poplar	*Populus* spp.	P	Low (E)	*	–	✓	0.74	–	3.72	–	–	–	–	–
Plum	*Prunus domestica*	S	–	DD	–	✓	0.06	–	–	0.16	–	–	0.12	0.36
Purpleheart	*Peltogyne paniculata*	–	–	–	–	✓	0.39	–	–	1.47	–	–	1.04	–
Redwood	*Sequoia sempervirens*	–	–	EN	–	✓	0.15	0.80	–	–	–	–	–	–
Rosewood	*Dalbergia* spp.	S,P	High (Af)	*	I (*Dalbergia nigra*), II (all the others)	✓	11.50	0.68	26.81	10.31	–	2.48	11.14	35.38

Table 1 (*continued*)

Common name	Scientific name	Product[a]	GTTN[b]	IUCN[c]	CITES	FSC[d]	Tot	T	BS	Bi	Ba	N	F	H
Sapele	*Entandrophragma cylindricum*	S,P	Low	VU	–	✓	1.49	0.80	6.35	–	–	0.32	–	0.36
Snakewood	*Brosimum guianense*	S	–	LC	–	✓	0.06	–	–	0.16	–	–	0.12	0.36
Spruce	*Picea* spp.	S,P	Low (E)	*	–	✓	18.13	78.54	–	–	100.00	–	–	–
Sweet Cherry	*Prunus avium*	–	–	LC	–	✓	0.35	–	1.75	–	–	–	–	–
Utile	*Entandrophragma utile*	S	High	VU	–	✓	0.19	–	0.22	–	–	0.76	–	–
Walnut	*Juglans* spp.	S,P	Low (C)	*	–	✓	3.29	0.34	2.74	3.11	–	2.48	9.40	0.36
Western Red Cedar	*Thuja plicata*	S	–	LC	–	✓	1.41	3.20	–	–	–	3.99	–	–
White Oak	*Quercus alba*	S	Medium	LC	–	✓	0.04	–	0.22	–	–	–	–	–
Ziricote	*Cordia dodecandra*	S,P	–	–	–	✓	0.24	–	0.88	0.16	–	–	0.12	0.36
Locally-Sourced Tonewood	–	–	–	–	–	–	0.41	–	0.98	–	–	1.08	–	–
Select Hardwood	-		–	–	–	–	1.36	–	–	0.82	–	5.72	0.58	–
Stained Hardwood	-		–	–	–	–	0.02	–	–	–	–	–	0.12	–

Where the header spans:

| Nomenclature | | | Sustainability | | | | Guitar components[e] | | | | | | | |

[a] Product: S = solid wood; P = plywood.

[b] Priority level according to the Global Timber Tracking Network (Cramm and Van Brusselen, 2019) and geographic origin: Af = Africa; As= Asia, Pacific & Oceania; C= Central and South America; E = Europe; N= North America.

[c] IUCN category: * = genus with at least one species in an IUCN category; DD: Data Deficient; EN: Endangered; LC = Least Concern; VU= Vulnerable.

[d] Availability of FSC-certified material (FSC, 2022).

[e] Frequency of use (% values): overall (Tot) and for each guitar component (T = top; BS = back and sides; Bi = bridge; Ba = brace; N = neck; F = fingerboard; H = headplate).

Table 2

Distinct commercial woods employed in acoustic guitars manufacturing within the genera *Acer, Dalbergia, Diospyros,* and *Swietenia.*

| Nomenclature | | | Sustainability | | | | Guitar components[e] | | | | | | | |
Common name	Scientific name	Product[a]	GTTN[b]	IUCN[c]	CITES	FSC[d]	Tot	T	BS	Bi	Ba	N	F	H
Ebony	*Diospyros* spp.	S	High (Af)	*	II (Madagascar)	✓	18.96	–	–	57.77	–	–	44.08	51.26
Ebony, Macassar	*Diospyros celebica*	–	Medium	VU	–	✓	0.65	–	0.22	2.29	–	–	1.62	–
Ebony, Malaysian	*Diospyros ebonasea*	S	–	–	–	–	0.02	–	0.11	–	–	–	–	–
Ebony, West African crelicam	*Diospyros crassiflora*	–	–	VU	–	✓	2.12	–	–	–	–	–	11.37	–
Mahogany	*Swietenia* spp.	S,P	–	*	II	–	19.39	8.79	31.95	–	–	56.53	–	0.72
Mahogany, Honduran	*Swietenia macrophylla*	–	Low	VU	II	✓	1.02	–	1.20	–	–	3.88	–	–
Maple	*Acer* spp.	S,P	High (E)	*	–	✓	1.75	0.80	4.38	0.33	–	3.24	0.23	–
Maple, Sycamore	*Acer pseudoplatanus*	S	–	LC	–	✓	0.11	–	0.55	–	–	–	–	–
Maple, Silver Leaf	*Acer saccharinum*	–	–	LC	–	✓	0.39	–	–	–	–	1.94	–	–
Maple, Hard Rock	*Acer saccharum*	–	–	LC	–	✓	0.30	–	–	–	–	1.51	–	–
Maple, Big Leaf	*Acer macrophyllum*	–	–	LC	–	✓	0.04	0.11	0.11	–	–	–	–	–
Rosewood	*Dalbergia* spp.	S,P	High (Af, As, C)	*	I (*Dalbergia nigra*), II (all the others)	✓	4.38	–	5.25	9.00	–	2.37	8.93	–
Rosewood, African Blackwood	*Dalbergia melanoxylon*	–	–	NT	II	✓	0.24	0.57	0.55	–	–	–	–	0.36
Rosewood, Brazilian	*Dalbergia nigra*	–	High	VU	I	–	0.24	–	0.88	–	–	–	–	1.08
Rosewood, Cocobolo	*Dalbergia retusa*	S	High	CR	II	✓	0.09	–	0.44	–	–	–	–	–
Rosewood, East Indian	*Dalbergia latifolia*	–	High	VU	II	✓	6.20	0.11	18.71	1.31	–	0.11	2.20	31.05
Rosewood, Guatemalan	*Dalbergia tucurensis*	–	High	EN	II	–	0.06	–	0.11	–	–	–	–	0.72
Rosewood, Honduran	*Dalbergia stevensonii*	–	High	CR	II	✓	0.06	–	0.33	–	–	–	–	–
Rosewood, Madagascar	*Dalbergia baronii*	–	High	VU	II	–	0.24	–	0.55	–	–	–	–	2.17

[a] Product: S = solid wood; P = plywood.

[b] Priority level according to the Global Timber Tracking Network (Cramm and Van Brusselen, 2019) and geographic origin: Af = Africa; As= Asia, Pacific & Oceania; C= Central and South America; E = Europe.

[c] IUCN category: * = genus with at least one species in an IUCN category; CR= Critically Endangered; EN: Endangered; LC = Least Concern; NT= Near Threatened; VU= Vulnerable.

[d] Availability of FSC-certified material material (FSC, 2022).

[e] Frequency of use (% values): overall (Tot) and for each guitar component (T = top; BS = back and sides; Bi = bridge; Ba = brace; N = neck; F = fingerboard; H = headplate).

European spruce, Euro alpine spruce, European high spruce and German spruce. Honduran mahogany (*Swietenia macrophylla*) was also indicated as Genuine mahogany while Australian blackwood (*Acacia melanoxylon*) was also referred to as Tasmanian blackwood. The Western red cedar (*Thuja plicata*) was also equivocally called Cedar even though it does not belong to the genus *Cedrus*. Worthy of note is also that some manufacturers created new names for particular situations, such as "Urban ash" to indicate ash wood derived from trees grown in urban areas.

Second, another common occurrence was the use of names that can be ascribed to different, and sometimes botanically unrelated, commercial woods. The two most notable examples found are "ebony" and "rosewood". The term "ebony" has been long referred to the genus *Diospyros* [30], which comprises over 700 species of which it is estimated that only about 30 yield timber of commercial interest [39]. However, the term is frequently used for dark-colored heavy and hard timbers belonging to other genera too [40]. The term "rosewood" has been conventionally used since 1800 to designate the *Dalbergia* genus which includes around 270 species distributed in the tropical regions of the world, but it is widely used for numerous timbers belonging to other genera too [40]. Currently, only a few dozen *Dalbergia* species are relevant in international commerce [41]. Although both terms are frequently used to designate a broad commercial category, and as such are presented in Table 1, they comprise dozens of distinct commercial woods with their own characteristics, value, geographical origins, and sustainability issues. However, only 13% of the ebonies and 62% of the rosewoods found in our survey could be attributed to a single species and therefore to a well-defined wood, while in the other 87% and 38% cases respectively, we had to refrain from going further than the genus (Table 2). The different cases encountered in the survey are further described.

Among the ebonies, we detected the use of several species: *Diospyros celebica, D. crassiflora,* and *D. ebonasea* (unconfirmed scientific name), while among the rosewoods *Dalbergia baronii, D. latifolia, D. melanoxylon, D. nigra, D. retusa, D. stevensonii* and *D. tucurensis*. More in detail, West African crelicam ebony (*Diospyros crassiflora*) is a tree native to equatorial west Africa that produces up to 80% processing waste in the production of guitars [42]. On the other hand, Malaysian ebony (*Diospyros ebonasea*) and Macassar ebony (*Diospyros celebica*) are both indigenous species of southeast Asia; the former is native to Malaysia, while the latter is endemic to the island of Sulawesi in Indonesia. *Diospyros celebica*, in particular, is an ebony that features a remarkable aesthetic variability of wood as its color may vary from a darker brown to reddish [34].

As for the rosewood, East Indian rosewood (*Dalbergia latifolia*) is a wood native to southeast Asia that has replaced *Dalbergia nigra*, which is native to Brazil, in the production of the back and sides of guitars. Cocobolo (*Dalbergia retusa*) is native to central America and its outstanding colors and grains are considered very attractive and contribute to its importance as a decorative rosewood [33]. Honduras rosewood (*Dalbergia stevensonii*) and Guatemalan rosewood (*Dalbergia tucurensis*) are both trees from Central and South America. *Dalbergia tucurensis* differs from the other species of the *Dalbergia* genus in its relatively low density and the absence of the distinctive odor that characterizes rosewoods [34]. Amongst African species, Madagascar rosewood (*Dalbergia baronii*) is endemic to Madagascar, while African blackwood (*Dalbergia melanoxylon*) is native to Central and Southern Africa. As its name suggests, African blackwood is characterized by a black wood color that is very unusual among woods belonging to the genus *Dalbergia* [34].

Furthermore, the survey detected similar situations for maples (*Acer*) and mahogany (*Swietenia*), wherein only 32.5% and 5% of cases respectively could be attributed to distinct commercial woods within the genus (Table 2). Contrary to ebonies and rosewoods, however, the commercial woods within the two genera are much less different from each other and only the term "mahogany" is frequently used for timbers belonging to other genera too. *Acer* includes 157 species distributed in the northern hemisphere [32]. Sycamore maple (*Acer pseudoplatanus*) is native to central and eastern Europe as well as southern Asia. Meanwhile, the Silver leaf maple (*Acer saccharinum*), Big leaf maple (*Acer macrophyllum*), and Hard rock maple (*Acer saccharum*) are original to North America. Of all maples, *Acer saccharum* has the greatest commercial relevance [34]. Concerning the genus *Swietenia*, it comprises three species of which Honduran mahogany (*Swietenia macrophylla*) is the most readily available one as it is widely cultivated in plantations [32]. The term "African mahogany" refers instead to *Khaya ivorensis*, but may also refer to *Entandrophragma utile*, which is more aptly called Sipo mahogany or Utile. Both share the same family, Meliaceae, with *Swietenia*. In the case of "Nato", we could not make a reliable attribution (Table 1). According to Ref. [31], it is in fact used for both the genus *Mora* and a good number of species belonging to the Sapotaceae family, whose pilot name is Nyatoh. A further example is the term "Grenadillo", which according to Ref. [31] other than *Platymiscium* spp. may also refer to the genus *Dalbergia*, but in this case, the attribution was straightforward since also the scientific name was indicated on the manufacturer's website.

Third, ambiguous nomenclature was also found in the use of vague names such as "selected hardwood'', "stained hardwood" or "locally sourced wood", for which the assignment of a corresponding taxon was impossible. Such commercial denominations clearly hinder the proper attribution of the wood species, and consequently a sustainability assessment.

Finally, it is noteworthy to report the recurrent use of the terms "flamed", "figured", "quilted" and "pomelle" which testifies the attention of guitar manufacturers in highlighting the selection of particular assortments well known for their aesthetic value.

3.2. Woods per guitar components

The investigation revealed that 62 different woods are currently used in the construction of acoustic guitars, and about 70% of them are tropical hardwoods. As shown in Fig. 3, three woods are significantly more used ($\chi^2 = 718.960$, p-value <0.001), namely Ebony (21.75%), Mahogany (20.41%), and Spruce (18.13%). Walnut, Maple, Ovangkol, Merbau, Okoume, Sapele, Western Red Cedar, Selected Hardwood, Nato, Richlite®, Koa, and HPL have, in order, an utilization rate between 4% and 1%.

Fig. 4 shows the wood distribution through the different guitar components. Since the woods used for the back and sides in a single guitar model were found to be always the same, the information on these two components is merged. Spruce (*Picea* spp., 78.54%) is the main wood used for the top ($\chi^2 = 2078.907$, p-value <0.001), and the only one for braces. As shown in Fig. 5, the woods used for the
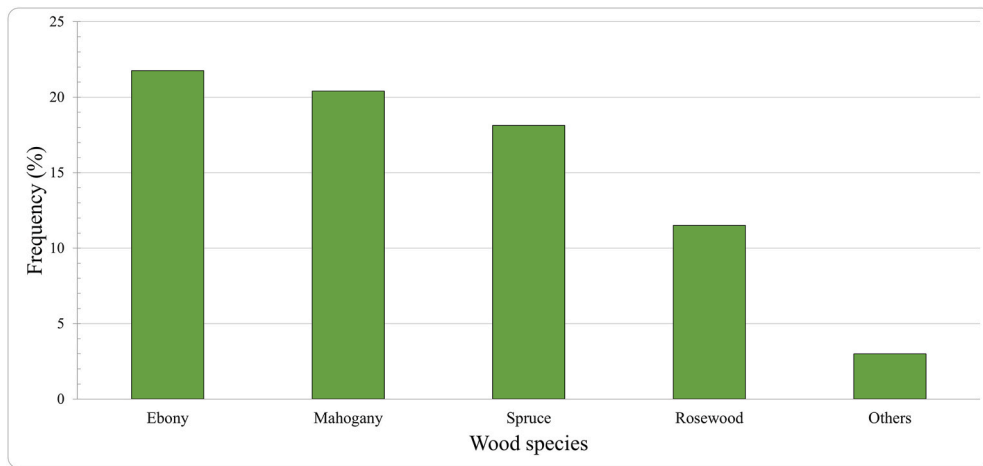
Fig. 3. Most commonly employed woods and wood-based composites in acoustic guitars. Only components with a utilization rate greater than 5% are shown.

top have a higher specific modulus (E/ρ) compared to the ones used for the back and sides. This is in accordance with what has been observed by Refs. [6,13], i.e. that a high Young's modulus value in relation to the density is a critical feature for the soundboard since it enables the wood to vibrate more easily, resulting in a more efficient sound emission.

Coming to other components, Mahogany (33.15%) and Rosewood (26.81%) are the woods of choice for back and sides ($\chi^2 = 446.034$, p-value <0.001), while Mahogany (60.41%) clearly prevails for the neck ($\chi^2 = 1364.312$, p-value <0.001).

An analysis of the Janka hardness of the woods used to build the different components (Fig. 6) reveals that the highest values correspond to bridges and fingerboards, in accordance with [19]. In fact, Ebony is the most widely used wood for the construction of bridges (60.07%), fingerboards (57.08%), and headplates (51.26%) (respectively, $\chi^2 = 20.512$, $\chi^2 = 963.961$, and $\chi^2 = 274.065$, with p-values always <0.001).

It is important to note that each component entails a different consumption of raw material depending on its dimension (cfr. [43]) and processing efficiency. Moreover, the consumption of each surveyed wood is dependent on the total number of pieces manufactured for each guitar model. However, the exploitation of large volumes of a species that do not appear critical in any index is not as impactful as the exploitation of a few cubic meters of a highly endangered species. Overall, for the purpose of our study, we considered sustainability indices that provide a consistent comparison between the different woods regardless of the consumed volumes.

Our survey also revealed a diffuse adoption of wood-based composites alongside the use of solid wood (Table 1). Agathis, Basswood, Birch, Lacewood, Meranti and Poplar in particular are exclusively used as engineered panels, while African mahogany, Koa, Mahogany, Mango, Maple, Nato, Ovangkol, Rosewood, Sapele, Spruce, Walnut, and Ziricote are present in both forms. A closer look at the engineered wood category (Table 3) reveals plywood as the most common product, mainly employed for tops, backs, and sides, followed by HPL (High Pressure Laminates) for headplates, and Richlite® for fingerboards and bridges. Among the surveyed materials, the faux tortoise is the only non-wood-based one.

Overall, engineered products and laminate materials are mainly found in low-priced acoustic guitars (Table 4). In fact, non-solid
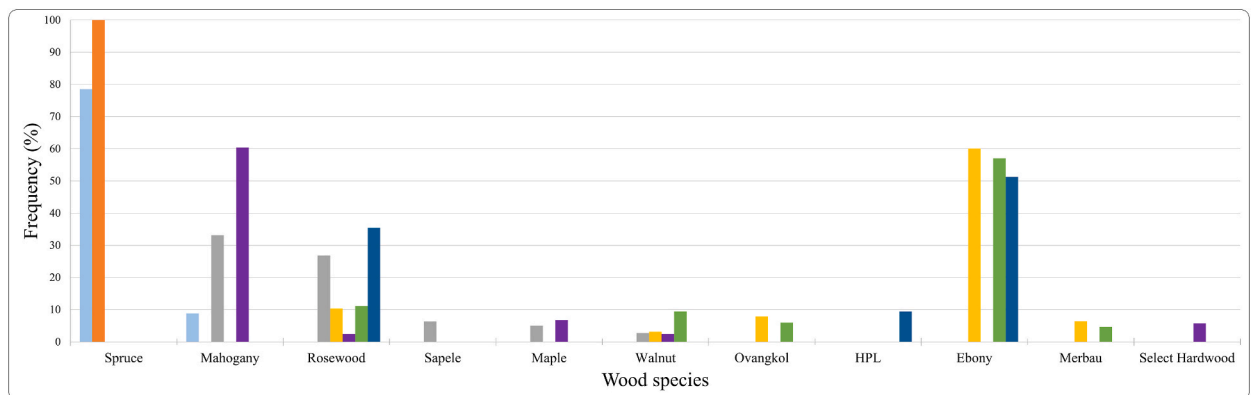
Fig. 4. Distribution of woods and wood-based composites per guitar component. Only components with a utilization rate greater than 5% are shown. Colors refer to guitar components: light blue = top; orange = brace; grey = back & sides; yellow = bridge; purple = neck; green = fingerboard; dark blue = headplate.
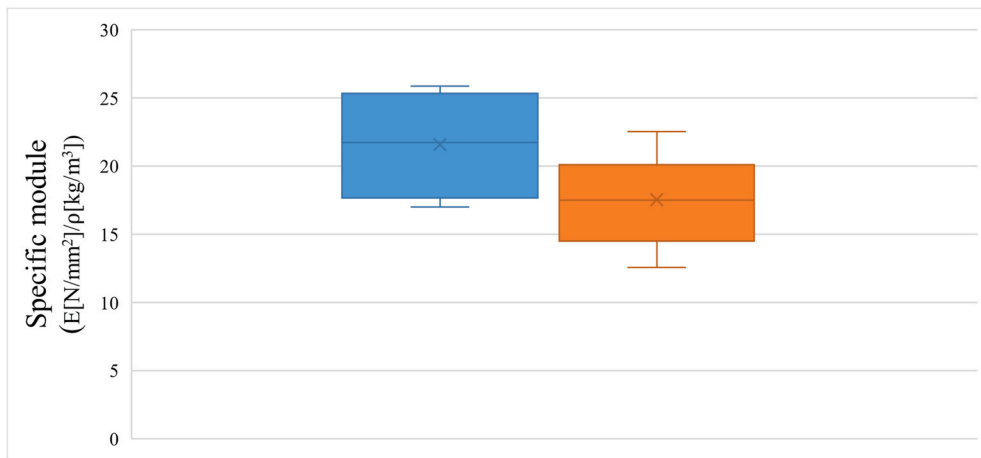
Fig. 5. Specific module (E[N/mm^2]/ρ[kg/m^3]) distribution of woods used for the top (blue) and the back and sides (orange). Only woods with a utilization rate greater than 1% are considered.
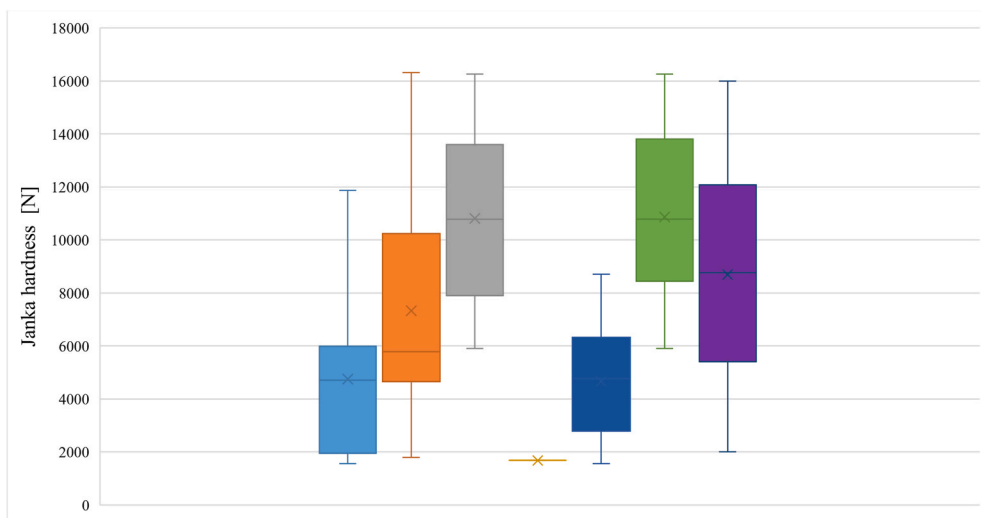

Fig. 6. Distribution of Janka hardness values [N] of the woods used in the different components. Blue = top; orange = back and sides; grey = bridge; yellow = brace; dark blue = neck; green = fingerboard; purple = headplate.

wood is almost exclusively present in the US$ 100–2000 price range where it accounts for 17.21% of the materials used in the construction of guitars, along with solid wood species like African mahogany, Ash, Dao, Eucalyptus, Katalox, Nato, Okoume, Ovangkol, Sapele, Walnut, Maple, and Utile. Maple, Walnut, Spruce, Ebony, Mahogany, and Rosewoods are commonly found in all price ranges. However, as the value raises, Honduran mahogany, Brazilian rosewood, Guatemalan rosewood, and Madagascar rosewood make their appearance. In particular, pre-CITES Brazilian rosewood constitutes the back and sides of the most expensive analyzed guitar ($124,999), and there is no doubt that this price is largely due to the use of this wood. As a result of high demand and increasingly limited supply, in 1992, Brazilian rosewood was the first wood to be CITES listed in Appendix I and it is now considered "Vulnerable" by the IUCN Red List. In fact, among all the wood species analyzed in this paper, Brazilian rosewood is the wood with the most critical sustainability issues.

3.3. Sustainability

Approximately 90% of the surveyed woods are potentially available with FSC certification [37], the only exceptions being Mahogany, Malaysian ebony, Indian laurel, Brazilian rosewood, Guatemalan rosewood, and Madagascar rosewood.

Besides the above-mentioned Brazilian rosewood, several woods found in our survey have sustainability issues, the most notable ones being those belonging to the genera *Dalbergia*, *Diospyros,* and *Swietenia*.

Since 2019, all *Dalbergia* species have been listed in CITES Appendix II, except for the previously discussed *Dalbergia nigra*, which is

Table 3
Wood-based composites.

Wood-based composites	Guitar components[a]							
	Tot	T	BS	Bi	Ba	N	F	H
African Mahogany (3-ply)	0.30	–	–	–	–	1.51	–	–
Birch Laminate	0.17	–	–	–	–	0.86	–	–
Engineered Hardwood	0.09	–	–	0.33	–	–	0.23	–
Faux Tortoise	0.02	–	–	–	–	–	–	0.36
HPL	1.00	0.68	1.53	–	–	–	–	9.39
Laminated Agathis	0.02	0.11	–	–	–	–	–	–
Laminated Basswood	0.09	–	0.44	–	–	–	–	–
Laminated Flame Maple	0.04	0.23	–	–	–	–	–	–
Laminated Lacewood	0.06	–	0.33	–	–	–	–	–
Laminated Mahogany	0.28	0.11	1.31	–	–	–	–	–
Laminated Nato	0.02	–	0.11	–	–	–	–	–
Laminated Ovangkol	0.09	–	0.44	–	–	–	–	–
Laminated Sapele	0.02	–	0.11	–	–	–	–	–
Laminated Spruce	0.17	0.91	–	–	–	–	–	–
Layered Koa (+Poplar)	0.11	–	0.55	–	–	–	–	–
Layered Maple (+Poplar)	0.02	–	0.11	–	–	–	–	–
Layered Sapele (+Poplar)	0.26	–	1.31	–	–	–	–	–
Layered Walnut (+Poplar)	0.15	–	0.77	–	–	–	–	–
Mahogany + Rosewood (5-ply)	0.48	–	–	–	–	2.37	–	–
Mahogany Pattern UTF (Ultra-Thin Film)	0.02	–	0.11	–	–	–	–	–
Mango Veneer on Meranti	0.02	0.11	–	–	–	–	–	–
Multi-piece inlay	0.02	–	–	–	–	–	–	0.36
Richlite®	1.06	–	–	3.60	–	–	3.13	–
Ziricote Fine Veneer	0.15	–	0.77	–	–	–	–	–

[a] Frequency of use (% values): overall (Tot) and for each guitar component (T = top; BS = back and sides; Bi = bridge; Ba = brace; N = neck; F = fingerboard; H = headplate).

in Appendix I. All the surveyed *Dalbergia* species are also included in the IUCN Red List. African blackwood (*Dalbergia melanoxylon*) is classified as "Near Threatened", East Indian rosewood (*Dalbergia latifolia*) and Madagascar rosewood (*Dalbergia baronii*) are "Vulnerable", Guatemalan rosewood (*Dalbergia tucurensis*) is "Endangered", and Cocobolo (*Dalbergia retusa*) and Honduran rosewood (*Dalbergia stevensonii*) are "Critically endangered". Furthermore, all of these are considered High priority by Ref. [36].

The *Diospyros* genus is a critical one too: in fact, all Madagascar species are listed in CITES appendix II and are considered of high priority by Ref. [36]. Among the surveyed species, *Diospyros crassiflora* and *Diospyros celebica* are considered "Vulnerable" by the IUCN Red List and the latter is of medium priority according to Ref. [36].

Regarding Mahogany, the entire *Swietenia* genus is included in CITES Appendix II, except for the wood from non-neotropical plantations. Honduran mahogany (*Swietenia macrophylla*), commonly cultivated in Asia, is reported as "Vulnerable" by IUCN and of low priority by Ref. [36].

Other commercially restricted genera include *Platymiscium* and *Fraxinus,* which however have only one species each listed in a CITES Appendix. In more detail, *Platymiscium parviflorum* is listed in Appendix II and is also considered low priority by Ref. [36], while *Fraxinus mandshurica* from the Russian Federation is included in the CITES Appendix III. In addition, the entire *Fraxinus* genus is considered low priority by Ref. [36], and, as well as *Platymiscium*, it comprehends several species listed in a critical IUCN Red List category.

Amongst the non-CITES listed genera, we found 15 wood species classified as at least "Vulnerable" in the IUCN Red list, and 19 included in the GTTN priority list. In particular, *Sequoia sempervirens* is "Endangered" on the IUCN Red list, while *Khaya ivorensis*, *Microberlinia brazzavillensis*, *Aucoumea klaineana*, *Entandrophragma cylindricum* and *Entandrophragma utile* are "Vulnerable". Finally, also the genera *Alnus*, *Betula*, *Eucalyptus*, *Panopsis*, *Palaquium*, *Populus*, *Picea,* and *Juglans* include species classified at least "Vulnerable" on the IUCN Red List. Regarding the GTTN priority list, as shown in Tables 1 and 2, 8 woods are high priority (*Khaya ivorensis*, *Terminalia superba*, *Acer* spp., *Shorea* spp., *Palaquium* spp. *Aucoumea klaineana*, *Pterocarpus soyauxii,* and *Entandrophragma utile*), 4 are medium priority (*Hymenaea courbaril*, *Intsia bijuga*, *Machaerium scleroxylon,* and *Quercus alba*) and 7 are low priority (*Microberlinia brazzavillensis*, *Betula* spp., *Eucalyptus globulus*, *Populus* spp., *Entandrophragma cylindricum*, *Picea* spp., and *Juglans* spp.). In total, 53 out of the 62 surveyed woods appear in at least one list, 17 are in two of them, and 12 in all three.

Finally, it is important to note that the three indicators adopted for evaluating conservation threats are in constant evolution and that species currently not listed on any of these references should not be considered exempt from any risk of vulnerability.

3.4. Alternative woods

The above-discussed environmental and commercial constraints affecting several of the typical woods used in acoustic guitars construction are increasingly pushing companies towards more sustainable and affordable alternative woods.

For example, although substitutes able to match the precious ebony in terms of mechanical and aesthetic properties are hard to find, cheaper guitars fretboards and bridges are frequently made of Merbau (*Intsia bijuga*), Ovangkol (*Guibourtia ehie*), Walnut (*Juglans* spp.)

Table 4

Distribution of woods and wood-based composites by guitars' price range. a Price ranges have been established arbitrarily by the authors on the basis of the prices of acoustic guitars available for sale. Values are expressed as percentages. b The sparkline graph shows the distribution of woods and wood-based composites within the four price ranges.

Woods and wood-based composites	Price range[a]				Sparkline Graphic[b]
	$100-2000	$2000-5000	$5000-10000	>$10000	
African Mahogany	0.14	0.21	-	-	
African Mahogany (3-ply)	0.07	0.10	-	-	
Alder	-	0.03	-	-	
Ash	0.07	0.03	-	-	
Australian blackwood	-	0.03	-	-	
Bald cypress	-	0.07	-	-	
Birch laminate	0.28	-	-	-	
Dao	0.07	-	-	-	
Ebony	2.60	12.64	3.50	0.66	
Ebony, West African crelicam	1.18	1.73	0.48	-	
Eucalyptus	0.38	0.03	-	-	
Faux Tortoise	-	0.03		-	
FSC® Certified Richlite®	1.52	-	-	-	
Grenadillo	-	-	0.03	-	
Hawaiian Koa	0.21	0.28	0.48	-	
HPL	1.59	-	-	-	
Katalox	0.21	-	-	-	
Koa Fine Veneer	0.10	-	-	-	
Laminated Agathis	0.03	-	-	-	
Laminated Basswood	0.14	-	-	-	
Laminated Flame maple	0.07	-	-	-	
Laminated Lacewood	0.10	-	-	-	
Laminated Mahogany	0.45	-	-	-	
Laminated Nato	0.03	-	-	-	
Laminated Ovangkol	0.14	-	-	-	
Laminated Sapele	0.03	-	-	-	
Laminated Spruce	0.28	-	-	-	
Layered Koa	0.17	-	-	-	
Layered Maple	0.03	-	-	-	
Layered Rosewood	0.31	-	-	-	
Layered Sapele	0.42	-	-	-	
Layered Walnut	0.24	-	-	-	
Locally-Sourced Tonewood	0.24	-	-	-	
Mahogany	7.34	8.59	1.70	0.03	
Mahogany + Rosewood (5-ply)	0.42	0.10	0.21	-	
Mahogany Pattern UTF (Ultra-Thin Film)	0.03	-	-	-	

Mahogany, Honduran	-	0.66	0.80	0.24	
Mango	-	0.07	-	-	
Maple	0.76	0.52	0.62	0.07	
Maple, Big Leaf	-	0.07	-	-	
Maple, Hard Rock	0.14	0.35	-	-	
Maple, Sycamore	-	0.03	-	-	
Nato	1.70	-	-	-	
Okoume	0.24	-	-	-	
Ovangkol	0.35	0.14	-	-	
Padouk	-	0.17	-	-	
Pau Ferro	0.31	-	-	-	
Plum	-	0.10	-	-	
Redwood	-	-	0.10	0.03	
Rosewood	2.29	1.52	0.66	0.03	
Rosewood, African Blackwood	-	0.03	-	-	
Rosewood, Brazilian	-	-	-	0.21	
Rosewood, Cocobolo	-	0.07	0.03	-	
Rosewood, East Indian	0.97	5.64	1.90	0.14	
Rosewood, Guatemalan	-	-	0.07	0.03	
Rosewood, Madagascar	-	-	0.21	0.07	
Sapele	1.00	0.31	-	-	
Select Hardwood	1.45	0.69	0.03	-	
Spruce	7.38	8.41	2.98	0.52	
Stained Hardwood	0.03	-	-	-	
Sweet Cherry	-	0.07	-	-	
Utile	0.10	0.07	-	-	
Walnut	3.12	0.52	0.03	0.03	
Western Red Cedar	0.03	1.45	0.07	-	
White Oak	-	0.07	-	-	
Ziricote	-	-	0.10	-	
Ziricote Fine Veneer	0.24	-	-	-	

and, on a smaller scale, Padauk (*Pterocarpus soyauxii*), and Katalox (*Swartzia cubensis*). The two latter are considered excellent substitutes for ebony bridges also by Refs. [9,19].

As a replacement for Koa (*Acacia koa*), a rare wood present in Hawaii only and threatened by animal grazing, Australian blackwood (*Acacia melanoxylon*) is used as a cheaper and more readily available excellent substitute [44].

Sapele (*Entandrophragma cylindricum*), Utile (*Entandrophragma utile*), and African mahogany (*Khaya ivorensis*) are African woods that not only share the same botanical family as true mahogany (*Swietenia* spp.) but also the appearance and are often referred to as "African mahogany". Long considered excellent substitutes for American mahogany, they are now affected by environmental constraints themselves, as evidenced by their listing as "Vulnerable" on the IUCN Red List. Nato, a more recent mahogany substitute currently used in the acoustic guitar sector, also includes several species, belonging to the *Palaquium* and *Payena* genera, listed in critical IUCN categories.

Brazilian rosewood (*Dalbergia nigra*) has always been considered the wood of choice for back and sides [45]. However, since its listing in CITES Appendix in 1992, guitar manufacturers have been forced to find worthy substitutes, first looking amongst the

numerous other valuable woods offered by the same genus. East Indian rosewood (*Dalbergia latifolia*) in the first place, but also Cocobolo (*Dalbergia retusa*), Honduran rosewood (*Dalbergia stevensonii*) and Guatemalan rosewood (*Dalbergia tucurensis*) have long replaced *Dalbergia nigra*. As shown in Table 2, rosewoods are also used for various other components. However, the recent inclusion of the whole genus in CITES Appendix II is increasingly driving attention toward the use of *Dalbergia* substitutes, notably Katalox (*Swartzia cubensis*), Jatoba (*Hymenaea courbaril*), Pau ferro (*Machaerium scleroxylon*) and Grenadillo (*Platymiscium* spp.), amongst which only the former is not listed in any of the above-discussed references.

In some cases, for the construction of the back and sides, rosewoods are replaced by more common woods such as Maple (*Acer* spp.) and Black walnut (*Juglans* spp.), well-known species largely planted for the numerous applications of their wood [46,47]. In this regard [24], show that in terms of sound perception, there is no relevant difference between these woods and rosewoods, suggesting that aesthetic qualities play a major role in the reputation of rosewood backs and sides. Furthermore, the rarer the woods are, the more valuable they are considered, as the exorbitant price of the above-mentioned guitar made with *Dalbergia nigra* suggests.

Overall, our survey shows that alternative woods are in substitution for species with mainly support and aesthetic functions, mostly presenting critical issues related to the sustainable management of the original populations or their legal supply. On the contrary, the most important part for sound quality, i.e. the top, is provided to a greater extent by one wood only, spruce, which at the moment does not present sustainability issues and therefore is not subject to the need of finding substitutes.

3.5. Environmental commitment

Numerous companies are committed to environmental actions and projects. Several manufacturers adopt FSC certification for at least some of the used woods. Noteworthy is the presence in one company of a "sourcing specialist" tasked with evaluating the environmental and economic health of a sourcing site to ensure the sustainability of the raw material. One guitar featured 100% responsibly sourced FSC-certified wood and Rainforest Alliance certification, while another model was presented as the first FSC-Certified and 100% plastic-free acoustic guitar. Forest certification is also a valuable means for increasing the green image of companies, with positive rebounds in terms of marketing [48].

Companies have also adopted reforestation initiatives. For instance, one company planted tens of thousands of birch and maple trees in Pennsylvania and contributed to planting Mahogany, Cedar, Cocobolo, Rosewood, and Teak trees in Nicaragua. Another company is involved in the Ebony Project, which consists in replanting and restoring ebony forests in Cameroon, to make the supply chain of West African ebony (*Diospyros crassiflora*) more sustainable. A company promoted the Koa and Hawaiian Forest Restoration project, which aims to restore and revitalize Hawaii's native Koa forests, now drastically reduced due to deforestation for cattle grazing and the introduction of invasive species. Through initiatives in Tanzania, a company contributed to the conservation of African blackwood (*Dalbergia melanoxylon*) by planting African blackwood trees and promoting responsible forest management to ensure a stable future supply.

A third measure is the use of salvaged wood, or the raw material coming from fallen trees or old buildings. An example is the Urban Wood initiative launched in cooperation with a company that provides tree maintenance and management services in California and Arizona. The wood from ash trees that had to be removed from urban areas was used in the construction of the backs and sides of acoustic guitars. Another company promoted a program aimed at encouraging the use of recycled wood and alternatives to rare species, together with the reduction of waste and harmful substances.

Fourth, some companies foster the use of temperate and local woods instead of tropical ones (more subject to sustainability issues). A remarkable example is a website on which customers can design their own guitars using European wood only.

Overall, although the occurrence of virtuous cases, there is generally potential for further improvement as compared to other sectors. For instance Ref. [29], have recently shown that several sport companies have been heavily focusing their brand awareness and marketing strategies on environmental sustainability.

4. Conclusions

Our research provided a novel overview of the actual use of wood in acoustic guitar manufacturing that enables drawing some suggestions on how to improve the sustainable use of wood in acoustic guitars. The approach used in this study may be applied to similar analyses in other wood sectors.

Results show that overall wood remains, by far, the material of choice for acoustic guitars, where a wide number of wood species was found to be used. Amongst these, there are a few predominant ones. Spruce (*Picea* spp.) is the wood of excellence for the top, while Ebony (*Diospyros* spp.), Mahogany (*Swietenia* spp.), and Rosewood (*Dalbergia* spp.) are the preferred ones for the other components.

Except for spruce, all the classic and more sought-after woods for acoustic guitar manufacturing are tropical ones and increasingly facing sustainability issues. Several manufacturers are involved in environmental projects and initiatives, which are well displayed on their websites. However, the adopted nomenclature is ambiguous in various cases, and for some endangered wood species, little information is provided about preservation. To address sustainability issues, many manufacturers have been shifting towards more sustainable, readily available, and affordable alternatives. For the same reason, the use of engineered wood instead of solid wood, in particular in lower-priced products, is becoming more common.

Keeping the pursuit of alternative wood species and increasing the efforts on environmental commitment and on promoting end consumer sustainability awareness can be relevant actions to further enhance the use of wood in a sector that already valorizes this renewable material. At the same time, by providing more information about the used species and adopting a more reliable nomenclature, manufacturers can raise awareness and educate customers about the great diversity and appeal of wood. Perhaps this can be

brought even further by focusing on the sound qualities of the top, the "tonewood", which is most commonly the sustainable spruce, while promoting the sustainability and aesthetic qualities of alternative woods for the backs and sides.

Author contribution statement

Silvana Calvano: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Francesco Negro: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Flavio Ruffinatto: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Daniel Zanuttini-Frank, Roberto Zanuttini: Conceived and designed the experiments; Wrote the paper.

Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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