An African violin – The feasibility of using indigenous wood from southern Africa as tonewood

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DATES:
Received: 19 May 2021
Revised: 02 Aug. 2021
Accepted: 16 Sep. 2021
Published: 29 Nov. 2021

HOW TO CITE:
Meincken M, Roux G, Niesler T. An African violin – The feasibility of using indigenous wood from southern Africa as tonewood. S Afr J Sci. 2021;117(11/12), Art. #11175. https://doi.org/10.17159/sajs.2021/11175

ARTICLE INCLUDES:
☒ Peer review
☐ Supplementary material

DATA AVAILABILITY:
☐ Open data set
☒ All data included
☐ On request from author(s)
☐ Not available
☐ Not applicable

EDITOR:
Michael Inggs

KEYWORDS:
wood for soundboards, spectral analysis, exotic wood, musical instruments, string instruments

FUNDING:
None

The wood used to make musical instruments needs to have particular properties. Depending on its function, such as a soundboard for string instruments or the body of a wind instrument, different properties are desirable to obtain the best musical quality. Several different classification schemes exist that correlate physical and mechanical properties of wood to define desirable ranges for tonewoods, and to allow suitable wood species to be chosen. The physical and mechanical properties of various wood species indigenous to southern Africa were characterised and then assessed in terms of their suitability for violin construction using these classification schemes. The results of this analysis show that the most suitable of the wood species assessed are yellowwood and sapele. These were subsequently used by a professional luthier to build an 'African' violin. The sound quality of this instrument was determined subjectively through performances to an audience and more objectively via spectral analysis of audio recordings. This analysis shows clear differences in the relative magnitude of the harmonics between the violin made from indigenous wood and an instrument made with conventional wood species. Despite the differences, yellowwood and sapele were found to be suitable tonewoods, resulting in an instrument with a unique sound.

Significance:

- Good quality violins are always made from spruce and maple wood, which have to be imported to South Africa – often at high cost. However, the growth conditions of most southern African wood species should make them suitable tonewoods. We showed that several species are suitable to be used as tonewoods and that the sound produced with such a violin is – although somewhat different – of high quality.

Introduction

Tonewoods are wood species that possess certain desirable properties that make them suitable for the construction of musical instruments, such as woodwind or string instruments. Any good tonewood should be radially cut, have an even-grain structure, be defect free and be dimensionally stable, i.e. not shrink or swell noticeably with environmental changes.[1] Soundboards – woods that should resonate in order to amplify the oscillation – of string instruments should be lightweight, but stiff enough to withstand the tension of the strings and propagate sound well in the grain direction. The speed of sound along the wood grain should be as high as possible and substantially higher parallel to the grain than perpendicular to the grain.[2] Pronounced density differences in the wood lead to a scattering of the soundwave; therefore, significant differences between heart- and sapwood, or early- and latewood, are not desirable. This should make (sub)tropical wood species good candidates for tonewood, because the lack of pronounced growth seasons results in wood with barely visible year rings and few density variations.

In this paper, we report on mostly indigenous southern African wood species that are suitable for string instruments of the violin family.

High-quality violins are made of the same wood species worldwide: spruce as the soundboard (top plate) and maple as the frameboard (back).[3] While guitar makers seem to be more adventurous in using alternative wood species, violin makers tend to use only these traditional wood species that often have to be imported at high cost. Good-quality wood is typically from colder regions, like Canada or the European Alps, where the trees grow more slowly, which results in a uniform wood structure with fewer density fluctuations.

Several classification schemes have been published that group wood species into clusters that indicate potential uses for the species and their physical and mechanical properties. Soundboards for a violin, for example, need to be good sound transmitters with a high radiation ratio (the speed of sound parallel to the grain divided by the density). Frameboards, on the other hand, should have a high Young modulus to give support to the soundboard, while still radiating sound well. Action wood, such as the keys and hammers in a piano, needs to be strong to withstand repeated use and woodwind instruments are typically made from a dense, finely structured wood that reflects the soundwaves well.

Yoshikawa[4] determined that all suitable soundboards for string instruments follow a regression line orthogonal to the regression line of frameboards when the transmission parameter cR is plotted against the antivibration parameter ρ/c (c: speed of sound, ρ: density, R: radiation ratio).

Wegst[5] developed a wider classification scheme for all musical uses, including string instruments, action wood, bows and woodwind. Based on wood properties – such as the speed of sound, elastic modulus and density – Wegst identified areas in these graphs that define suitable wood species for certain purposes. Soundboards, for example, need to have a high speed of sound with a reasonably low density (to minimise weight) and an acceptable Young modulus to provide strength.

Bucur[2] published an extensive review of the field detailing the required wood properties for musical instruments in his book *Acoustics of wood* where he discussed the physical and mechanical properties that make wood suitable as tonewood.

None of these classification schemes, however, includes southern African wood species. We characterised several wood species using all relevant mechanical and physical properties and aligned these with the classification schemes described above. The two most suitable species (for the soundboard and frameboard) were then chosen for construction of a full-sized violin.

Luthiers regard the radiation ratio[6] (speed of sound parallel to the grain divided by the density) as the most crucial property and its value should be as high as possible.[7] In good instruments, it can reach values of around 15.[8] However, equally important are dimensional stability, anatomical wood structure and wood elasticity, as they all affect the way the sound wave propagates through the wood.

Nevertheless, the quality of the instrument depends as much on the skill of the luthier as on the wood properties, which makes it challenging to assign sound quality to wood properties alone. Therefore, we sought the help of one of South Africa's best luthiers – Hannes Jacobs – to make the violin. This ensured that the quality of the instrument would be comparable to good-quality commercial instruments. Our instrument, named the 'African violin', was then compared to a violin made from traditional wood species by the same luthier, presumably with the same methodology.

The sound quality of the two violins was determined by computing audio frequency spectra of a set of single notes to analyse the location and amplitude of resonance peaks – or overtones – that are discernible. The aim was a quantitative rather than a qualitative comparison between the two instruments made by the same luthier, but from different wood species.

Although many publications have discussed the quality of violins, most use a descriptive terminology in which listeners use adjectives to describe the sound – to quantify differences between instruments.[9] Generally, it is accepted that a good sound consists of many harmonics at higher frequencies. Meinel[10] recorded audio signals for different violins of known quality – a Stradivarius and a cheaper instrument – and attempted to define the sound quality through the differences observed in the frequency spectra. His main findings were that a 'good' instrument has high amplitudes in the lower frequency range, low amplitudes around 1.5 kHz, which results in a 'nasal' sound, a strong peak in the region of 2–3 kHz and low amplitudes above 3 kHz. This study was taken further by Gabrielsson and Jansson[11], Jansson[12] and Dünnwald[13] who refined the definitions of desirable frequency bands somewhat, but largely agreed with the findings in Meinel's[10] study.

Materials and methods

Wood selection and characterisation

Wood was sourced from Stander Houtverkope in Knysna and Rare Woods in Cape Town. The following wood species indigenous to southern Africa were characterised: yellowwood (*Podocarpus latifolius*), candlewood (*Pterocelastrus tricuspidatus*), hardpear (*Olinia ventosa*), quar (*Psydrax obovata*), stinkwood (*Ocotea bullata*), and Cape beech (*Rapanea melanophloeos*). Furthermore sapele (*Entandrophragma cylindricum*) from western Africa and blackwood (*Acacia melanoxylon*) were included in the study. Although blackwood originates from Australia, it has been established in the natural forests of the southern Cape since the early 1900s and forms a valuable resource for the local woodworking industry.

For comparison, Italian spruce (*Picea abies*) and maple (*Acer platanoides*), tonewood typically used to make violins, were obtained from the luthier and also characterised. Hereafter, all species are referred to by their common names.

The moisture content (MC) and air-dry density (ρ_{ad}) were determined from 10 wood blocks per species that were air-dried and stored in a conditioning room at 20 °C and 65% relative humidity for 2 months before analysis. All results are reported as average values. The MC was determined as

$$MC = 100\% * (m_{ad}-m_0)/m_0$$

and the air-dry density was determined as

$$\rho_{ad} = m_{ad}/V_{ad}$$

where m_{ad} = air-dry mass, m_0 = oven-dry mass and V_{ad} = air-dry volume.

The acoustic properties were determined at three different positions on two conditioned boards per species with the dimensions of 40 x 15 x 2 cm^3 and are reported as average values.

The sound velocity (c_s) was determined with ultrasound waves that are transmitted and received with two probes over a known distance (l) in the time (t) as $c_s = l / t$. The MC is used as a correction value to determine the accurate speed of sound.

In these experiments, a Lucchi meter was used, which is the instrument typically used by luthiers for accurate measurement of smaller wooden pieces.

From the sound velocity and the wood density, several other properties can be calculated, such as the specific Young modulus, $E = c_s^2 {}_* \rho$, and the radiation ratio, $R = c_s/\rho$ – properties which are used by the different classification schemes.

Wood classification

The classification schemes reported by Wegst[5] and Yoshikawa[4] were used to identify the most suitable species for the construction of a violin. Wegst plotted various physical and mechanical properties against each other – such as the Young modulus, or the sound velocity, as a function of the density – and identified areas of desirable characteristics for different tonewood uses. Yoshikawa found that the plots of the transmission parameter $c_s R$ as a function of the antivibration parameter ρ/c_s for the soundboards and frameboards of string instruments are linear and orthogonal.

The relevant properties of the wood species analysed in this study were fitted into these classification plots, and the species that best met the requirements were identified.

The violin

A full-size violin was made from the most suitable species for soundboard and frameboard by an established luthier in South Africa, Hannes Jacobs. The sound produced by this instrument was then compared to that of a control instrument made by the same luthier, but with conventional wood species, namely spruce and maple.

Sound analysis

Spectral analysis of the audio signals produced by both violins was performed on set of single notes to allow objective comparison of the produced harmonics. The violins were fitted with the same type of strings and played by the same person with the same bow.

Recordings were made in a studio at the Department of Music at Stellenbosch University with Sennheiser MKH 8020 omnidirectional microphones and a Sound Devices MixPre 10 T multitrack recorder at a sampling rate of 96 kHz with 24 bits per sample. The main microphone was placed 600 mm above the instrument and a control microphone was placed 600 mm in front of the musician on the same height as the violin.

The segmentation of the recordings into individual notes was accomplished using the open-source audio editor Audacity. Spectral analysis was performed using GNU Octave. The audio data of each note was divided into 16 384 sample (171 ms) frames with a 50% overlap. After application of a Hamming window, the power spectral density was computed for each frame using the fast Fourier transformation. Finally, these power spectra were averaged over all analysed frames and the amplitudes normalised to the highest spectral peak.

Frequency spectra were plotted and compared using Origin.

Results

Wood selection

Table 1 shows the physical and mechanical properties of all analysed wood species. Rows indicating the two species commonly used for violin making, spruce and maple, are shaded. Both wood species were supplied by the luthier and are high quality tonewood. The spruce, which is used for the soundboard, has a low density and high Young modulus, giving it stability while not making it too heavy. The sound velocity along the grain (II) is high with a ratio of sound velocity parallel and perpendicular (⊥) to the grain of approximately 3. The resulting radiation ratio – the ratio of sound velocity along the grain to the density – is high with a value of $R=13$. The maple wood used for the frameboard (back plate) and the ribs has a higher density and Young modulus, giving stability to the instrument without adding too much weight. It has an acceptably high sound velocity and radiation ratio.

The southern African wood species are sorted according to their density. Candlewood and quar have very high densities, which makes them too heavy to be used for the instrument body, but they present a feasible option for accessories, such as the fingerboard or the bow. The high densities also lead to a low radiation ratio, making them unsuitable as tonewood.

Yellowwood and blackwood showed the highest radiation ratio among the analysed wood species – although significantly lower than the Italian spruce – with reasonably low densities, making them suitable to be used as soundboards. Blackwood also has a very high Young modulus, which together with the acceptable density makes it an interesting alternative as a soundboard. The lower radiation ratio of these wood species may, however, result in a duller sound, because fewer harmonics at high frequencies can be expected.

Stinkwood, hardpear, sapele and Cape beech all have higher densities than yellowwood and blackwood, acceptable Young moduli, and radiation ratios comparable to maple, which makes them suitable as frameboards.

The properties used by Yoshikawa[4] for the acoustical classification of various wood species are the transmission parameter, which he defined as c*R, and the antivibration parameter, defined as ρ/c. He plotted these properties for various wood species typically used for musical instruments and found that most of the wood species used for soundboards lie on a regression line that shows decreasing c*R with increasing ρ/c, while most of the wood species used for frameboards are located on a regression line that is nearly orthogonal to the regression line of the soundboards.

None of the values determined for the southern African species lie directly on these lines, but some are reasonably close. Based on this classification scheme, the most suitable species for the soundboard are blackwood, followed by yellowwood, stinkwood, Cape beech, hardpear and sapele, although the high density of the latter four might lead to an excessive weight of the instrument. The only feasible wood species for the frameboard based on this classification is sapele.

Wegst[5] plotted several relevant physical properties of various wood species against each other and found that the species known to be suitable for certain end uses – such as the violin front, the back plate and the violin bow – form well-defined clusters. We utilised the classification based on the Young modulus and density, as illustrated in Figure 2. In the original classification, the areas suitable for woodwind, piano action wood etc. were also included in the plot. For the purpose of this study, however, only the areas relevant to string instruments were considered.

Soundboards should have a low density and a high Young modulus, while frameboards tend to have a somewhat higher density and Young modulus, to add stability to the instrument. Based on this classification scheme, suitable wood species for the soundboard would be yellowwood and blackwood, while suitable species for the frameboard would be sapele, Cape beech, stinkwood and hardpear. Quar and candlewood would be ideal for violin bows, or accessories, such as the fingerboard.

Based on the two classification schemes, the physical properties and the visual appearance of the wood (i.e. the boards with the best radial cut and the straightest grain), it was decided to make a violin using yellowwood for the soundboard and sapele for the frameboard, neck and ribs. Figure 3 shows the first African violin. The wood was not stained, so the colour difference between the lightly coloured yellowwood and the reddish, dark sapele wood is maintained.

Table 1: Physical properties of the conventional tonewoods and southern African wood species

Species	r_{ad} (kg/m³)	$c_{\perp}$	$c_{\parallel}$	Ratio $c_{\parallel}/_{\perp}$	E (Gpa)	E/r	R	c/r	ρ/c	c*R (10⁵)
Italian spruce	423	1949	5588	2.87	13.21	0.03	13.2	13.21	0.08	7.38
Maple	626	1598	4820	3.02	14.54	0.02	7.7	7.70	0.13	3.71
Quar	963	1371	5042	3.68	24.49	0.03	5.24	5.24	0.19	2.64
Candlewood	949	1056	4759	4.51	21.49	0.02	5.01	5.01	0.20	2.39
Hardpear	740	2200	5560	2.53	22.57	0.03	7.62	7.62	0.13	4.23
Stinkwood	720	1700	5400	3.18	21.00	0.03	7.50	7.50	0.13	4.05
Sapele	680	1800	4700	2.61	15.02	0.02	6.91	6.91	0.14	3.25
Cape Beech	670	1200	5000	4.17	16.25	0.03	7.69	7.69	0.13	3.85
Blackwood	600	1900	5650	2.97	19.15	0.03	9.42	9.42	0.11	5.32
Yellowwood	505	2000	5000	2.50	12.63	0.03	9.90	9.90	0.10	4.95

r_{ad}, air-dry density; $c_{\perp}$, sound velocity perpendicular to the grain; $c_{\parallel}$, sound velocity parallel to the grain; E, Young modulus; R, radiation ratio

Note: Shading indicates the species commonly used for violin making.

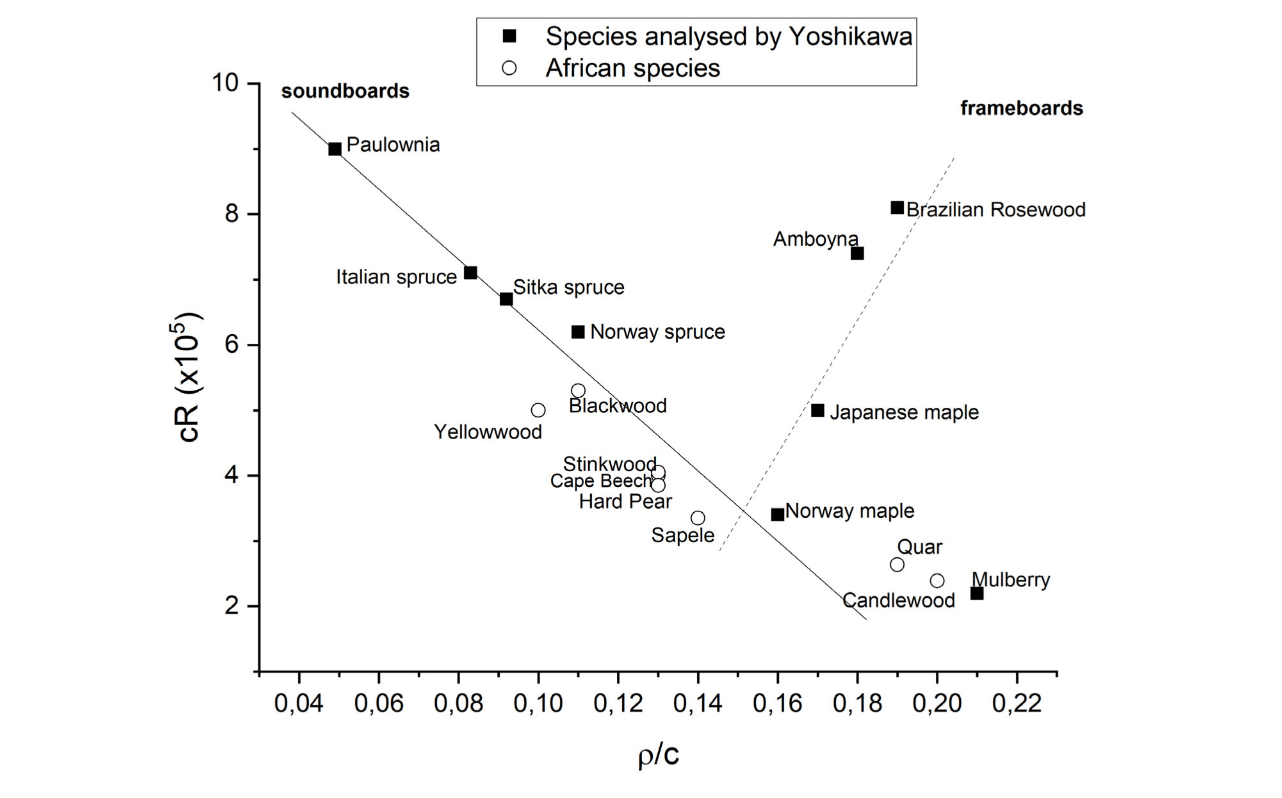

Figure 1: Acoustical classification suggested by Yoshikawa[4]. The regression lines indicate the properties of typical soundboards and frameboards, when the transmission parameter (cR) is plotted as a function of the antivibration parameter (ρ/c). Full squares indicate species reported in his study, while open circles represent the southern African species. Reference values sourced from Yoshikawa[4].

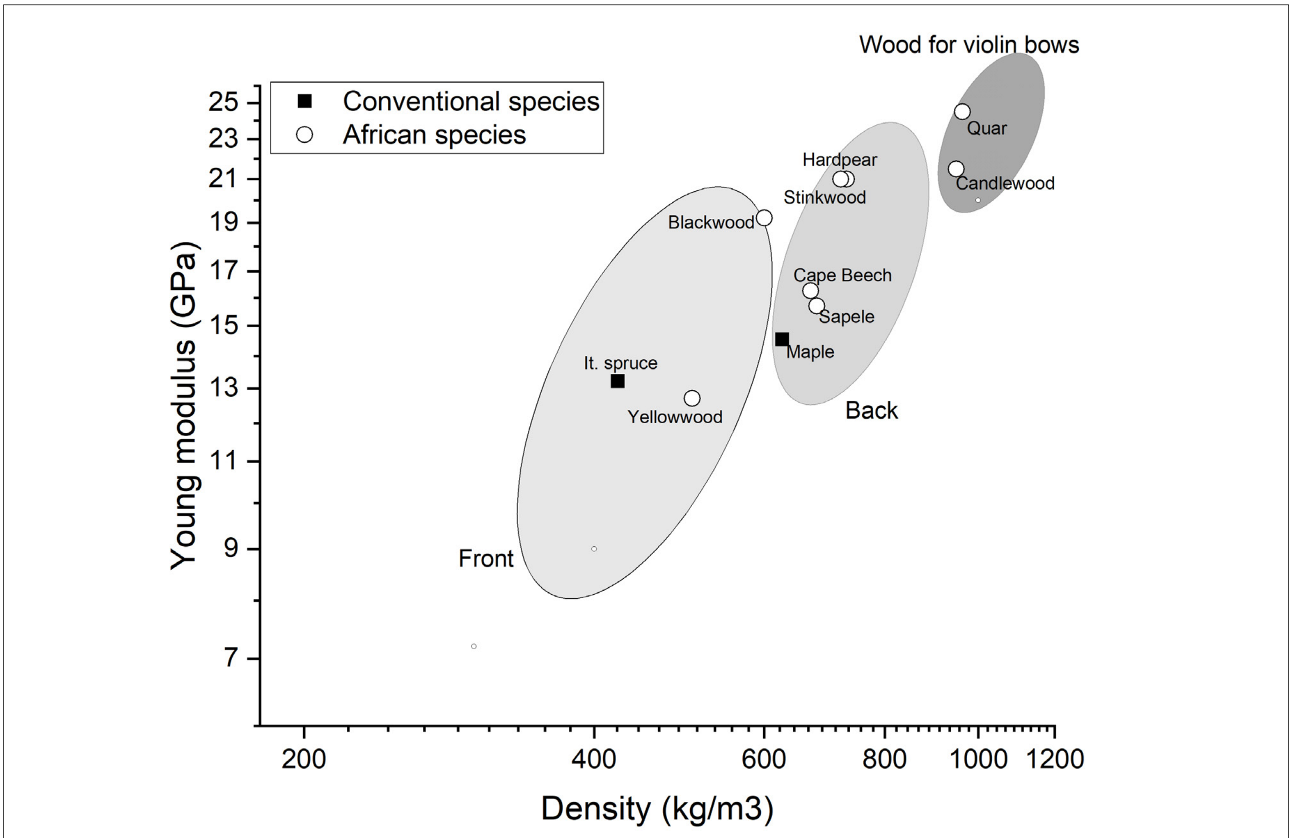

Figure 2: Classification suggested by Wegst[5]. The Young modulus E is plotted against the density ρ on a logarithmic scale. The highlighted areas indicate regions with suitable properties for soundboards (violin front), frameboards (violin back) and violin bows. Reference values sourced from Wegst[5].

Figure 3: The African violin made from yellowwood (soundboard) and sapele (remainder of the instrument).

A second violin will be made from blackwood for the soundboard, hardpear for the frameboard and sapele for the ribs and neck in a future project.

Due to the higher density of yellowwood and sapele compared to spruce and maple, the violin is a little heavier than conventional violins, weighing 540 g. In comparison, the conventional violin used for a comparison in this study weighs 458 g. All players noticed the extra weight, but did not experience it as a hindrance in playing the instrument.

Sound analysis

The violin was played by various musicians on separate occasions, and all agreed that its sound is quite different from that of most other violins. The general assessment was that it has a very full, powerful sound with a strong lower register that projects well through the room. Given the lower radiation ratio of yellowwood compared to spruce, it was expected that it would not resonate as well as a conventional violin at higher frequencies.

Generally, the sound quality of an instrument can be described by the number of harmonics, or overtones. The more harmonics there are, the fuller the sound. Meinel[10] defined four frequency regions that add to the quality of sound:

1. The harmonics below 1 kHz should have high amplitudes, which results in a 'sonorous sound that carries well'.
2. The amplitudes around 1.5 kHz should be low, to prevent a 'nasal' character.
3. High amplitudes between 2 kHz and 3 kHz result in 'agreeable, bright' sound.
4. Small amplitudes for frequencies above 3 kHz result in a 'soft, pure' sound.

For the sound analysis, empty strings and the high E6 (an octave above the empty E string) were played for as long and as uniformly as possible and each note was repeated 10 times. The average power spectrum was computed for each note and used to compare the sound of the African violin with that of a 'conventional' violin that was comparable in all other aspects, except the wood species used for its construction. The same person played both violins with the same bow.

The normalised power spectral magnitudes were plotted as a function of the frequency and the peaks clearly show the dominant harmonics. Spectral power is the squared amplitude, which is typically represented on a logarithmic scale, as illustrated in Figure 4.

The frequency content is represented as a power spectrum, which is a standard representation in digital signal processing.[14] Plotting the spectral power rather than the amplitude (the square root of the power magnitude) of the complex spectrum makes smaller harmonics less visible and only the predominant harmonics appear as peaks. In addition, if the spectral power is plotted on a linear rather than the usual logarithmic scale, the main harmonic peaks are even more prominent, which makes a direct comparison easier.

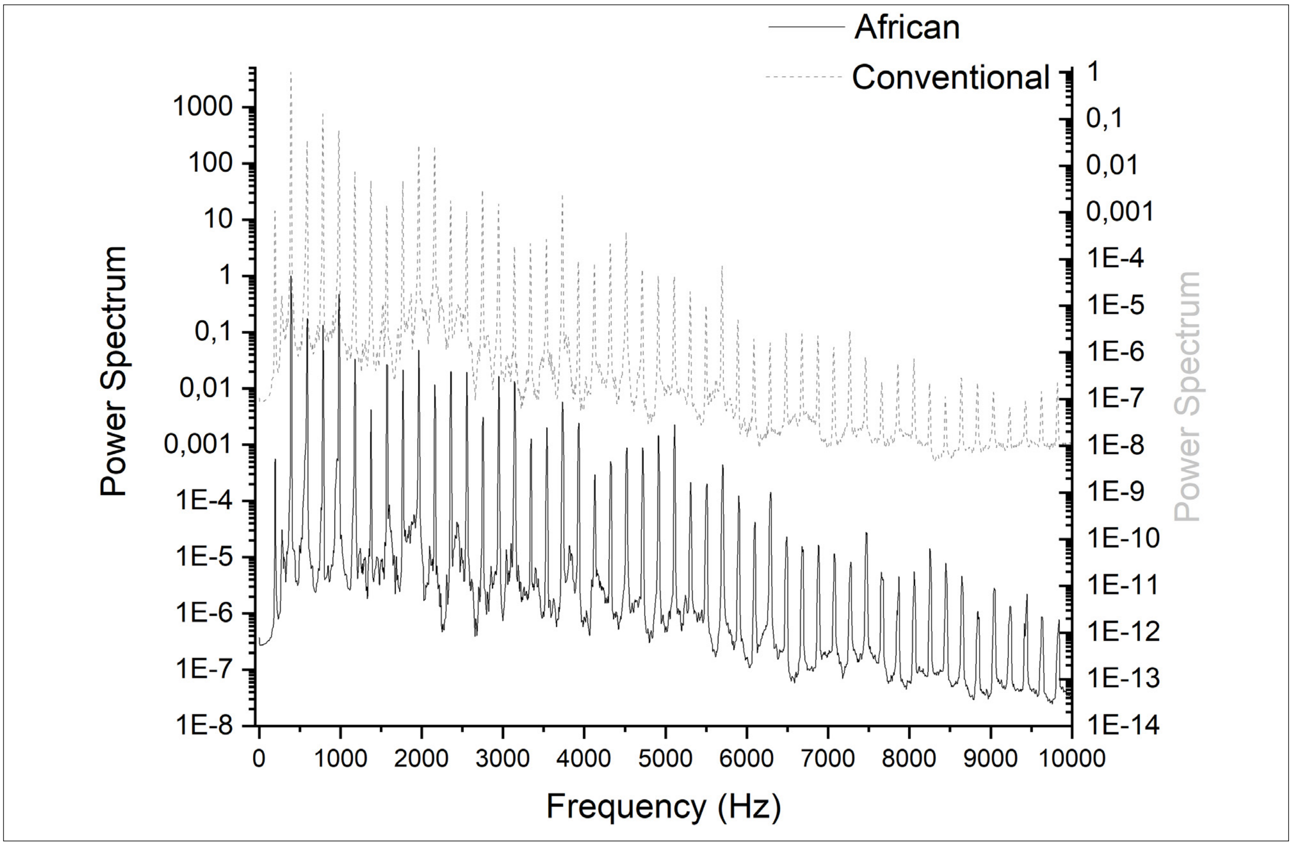

Figure 4: The sound signal (here G3) after Fourier transformation showing the normalised power spectrum on a logarithmic scale as a function of the frequency. The African violin is represented by the black line and the conventional violin by the dashed grey line.

The harmonic peaks continue throughout the high-frequency ranges and occur at multiples of the base frequency. In the linear representation, the frequency range was, however, limited to the values where significant peaks were present in the linear representation.

Figure 5a–e show the predominant harmonics in the linear spectra for both violins when the empty strings (G3, D4, A4, E5) and the octave above the empty E string (E6) were played. The fact that a linear scale is used means that only the most dominant peaks are clearly visible, while many smaller peaks disappear. In all graphs, the African violin is represented by a black line in the bottom half of the graph and the conventional violin by a dashed, grey line at the top half of the graph.

Both violins show higher amplitudes at low frequencies and smaller amplitudes around 1.5 kHz. However, the resonance frequencies of the African violin are visibly different from those of the conventional violin. It has stronger harmonics in the low-frequency range, which result in the full sound that carries well throughout the room. It also shows more overtones at higher frequencies. Especially for the G and D strings (Figure 5a and 5b), the frequency range between 2 kHz and 3 kHz, which is associated with a bright sound, is more pronounced for the African violin. However, harmonics in this frequency range are more pronounced for the conventional violin for the A and E strings (Figure 5c and 5d). For frequencies above 3 kHz, the African violin shows clearly higher amplitudes, which gives it a somewhat harsh sound, whereas the lower amplitudes of the conventional violin result in a soft sound.

The physical properties listed in Table 1 – especially the radiation ratio R, which is significantly lower in yellowwood than in spruce – suggest that the African violin would radiate sound less well in the high-frequency range. Contrary to this expectation, the African violin shows larger resonance peaks at high frequencies than does the conventional violin. This becomes even more evident if the amplitude rather than the power spectrum is plotted over a larger frequency range, as displayed in Figure 6, which shows the harmonics of the E string.

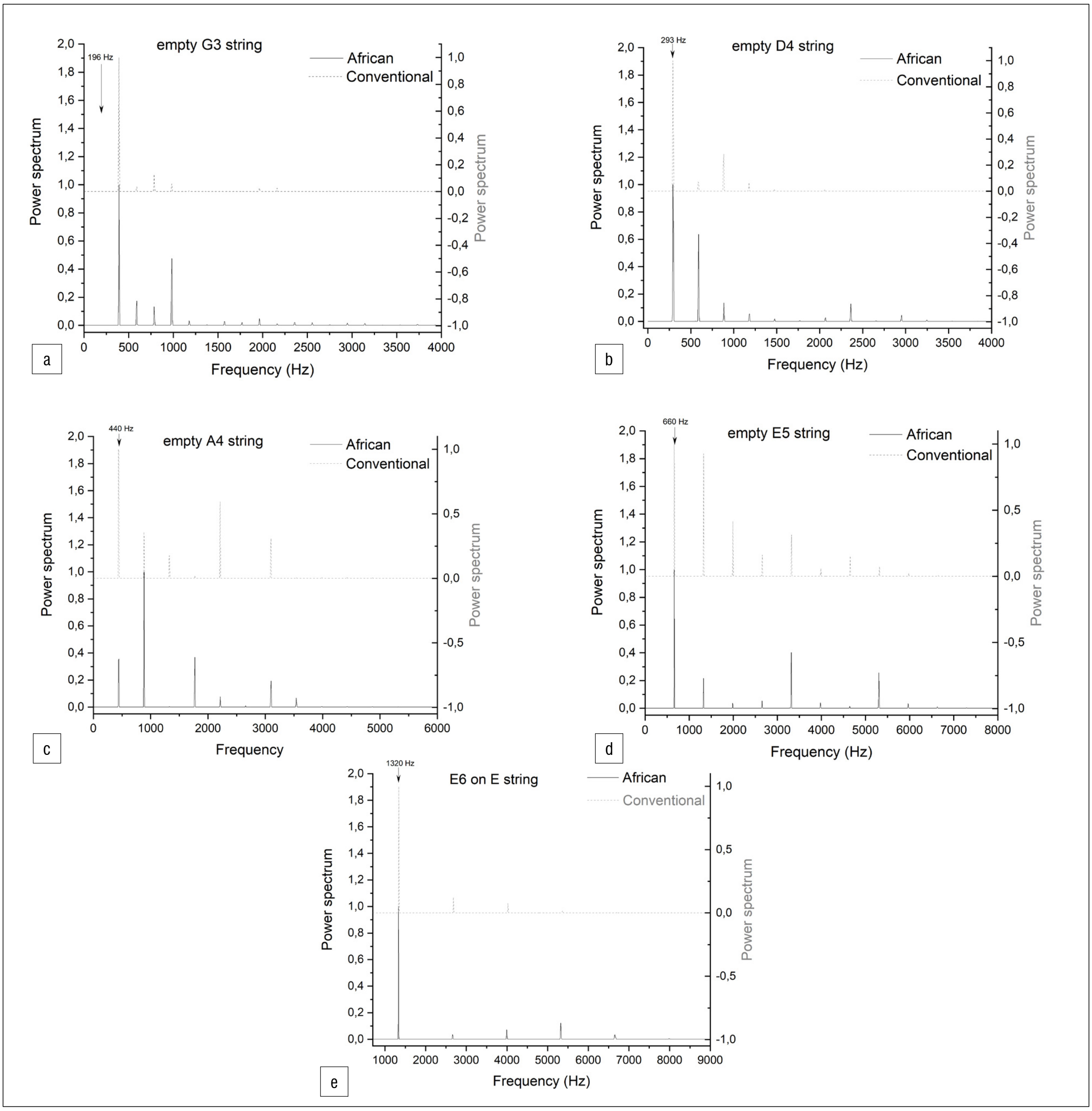

Figure 5: The predominant harmonics of both violins audible when the empty (a) G, (b) D, (c) A and (d) E strings are played, as well as the higher E6 (e). The base frequencies are indicated by an arrow.

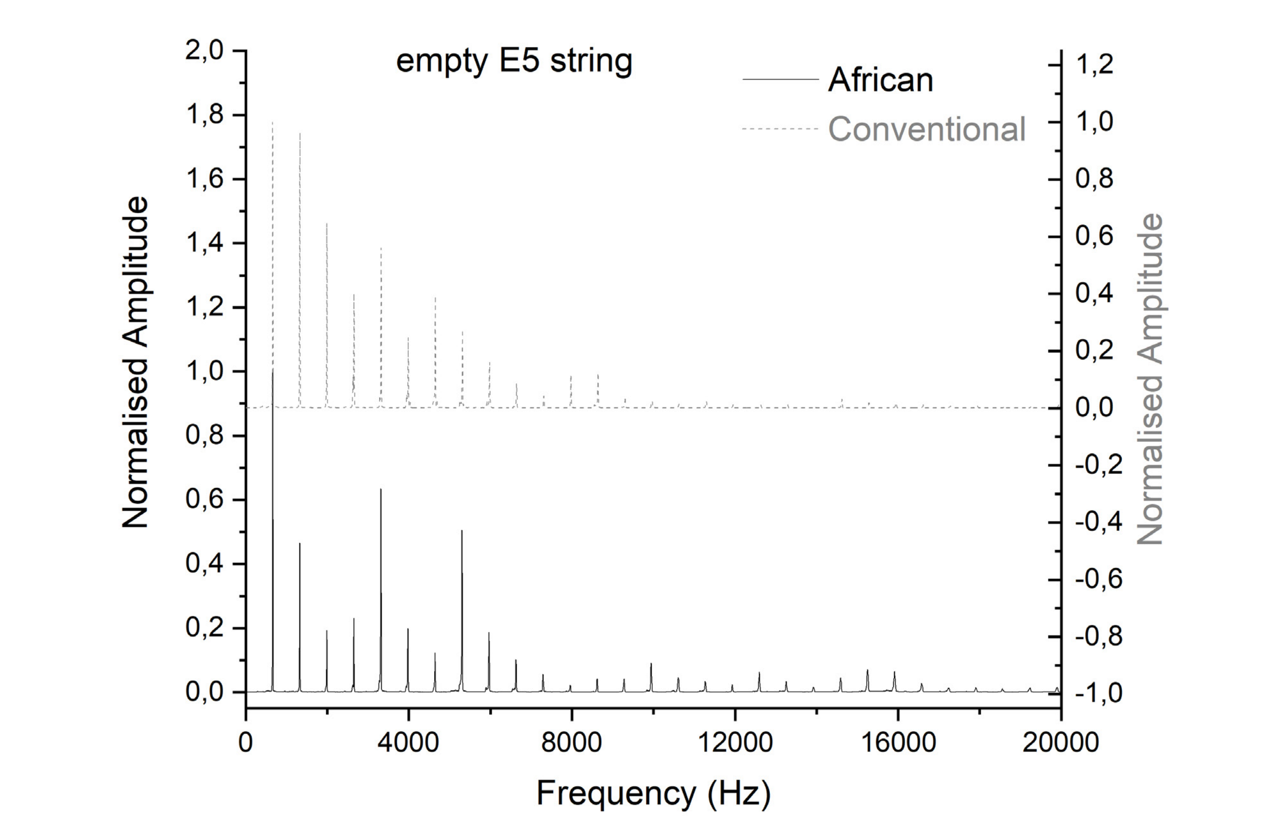

Figure 6: Normalised amplitude for both violins when the empty E string is played.

It can be seen that the amplitudes of the different harmonics below 8 kHz are different for the two violins, which results in the different sound. Surprisingly, the African violin shows significantly higher harmonics at frequencies above 10 kHz. This was not really expected, because yellowwood has a significantly lower radiation ratio (9.9) than the Italian spruce (13.2).

The aim of this project was to identify indigenous southern African wood species that are suitable as tonewood, and four species were identified: yellowwood and blackwood as possible soundboards and sapele and hardpear as possible frameboards. A first violin was made by a professional luthier from yellowwood and sapele and a second violin will be made as an ongoing project from blackwood and hardpear. Preliminary sound analysis showed that the African violin has a distinctly different sound with a powerful lower register and surprisingly many harmonics at higher frequencies. A more thorough sound analysis of both African violins will be performed in a future study.

Conclusions

The acoustic properties of indigenous wood species from southern Africa were characterised and fitted into two established classification schemes used to identify suitable tonewoods for string instruments. Several wood species showed promise for use as soundboards and frameboards. Based on these results, a violin was made using yellowwood and sapele.

A comparative spectral analysis with a control instrument showed clear differences in the acoustic radiation pattern between the two violins. The African violin displayed larger harmonics at low and high frequencies for the G and D strings which result in a full sound that carries well through the room. For the higher notes – especially the E string and the E6 – high-frequency harmonics were lower in amplitude for the conventional violin, which results in a softer sound. Despite the differences, both violins were perceived to produce good sound quality. The difference in sound can be attributed to the wood species that were used to make the instruments and the results show that yellowwood and sapele are clearly suitable to be used as tonewoods and produce an instrument with a beautiful, though slightly different sound. The African violin has a significantly stronger sound in the lower frequencies that carries very well through the room. It also showed more harmonics with higher amplitudes in the high frequencies, which gives it a harsher sound than the conventional violin. Yellowwood and sapele can be used to make string instruments with a sonorous, strong sound.

Acknowledgements

We thank Hannes Jacobs for producing a wonderfully unique violin and Gretna Heynike for providing the control violin and playing the two violins for the recording.

Competing interests

We have no competing interests to declare.

Authors' contributions

M.M.: Project management, conceptualisation, methodology, sample analysis, data collection, writing, student supervision. G.R.: Data collection, validation, writing. T.N.: Data processing and analysis, validation, writing.

References

1. Richter HG. Holz als Rohstoff fuer den Musikinstrumentenbau [Wood as a raw material for making musical instruments]. Celle: Moeck; 1988. German.
2. Bucur V. Wood species for musical instruments. In: Acoustics of wood. 2nd ed. Heidelberg: Springer; 2006. p. 173–215. https://doi.org/10.1007/3-540-30594-7
3. Hutchins CM. The acoustics of violin plates. Sci Am. 1981;245:170–186. https://doi.org/10.1038/SCIENTIFICAMERICAN1081-170

4. Yoshikawa S. Acoustical classification of wood for string instruments. J Acoust. 2007;122:568–573. https://doi.org/10.1121/1.2743162
5. Wegst U. Wood for sound. Am J Bot. 2006;93:1439–1448. https://doi.org/10.3732/ajb.93.10.1439
6. Schelleng JC. Wood for violins. J Catgut Acoust Soc. 1982;37:8–19.
7. Barlow CY. Materials selection for musical instruments. Proc Inst Acoust. 1997;19:69–78.
8. Fritz C, Blackwell AF, Cross I, Woodhouse J, Moore BCJ. Exploring violin sound quality: Investigating English timbre descriptors and correlating resynthesized acoustical modifications with perceptual properties. J Acoust. 2012;131:783–794. https://doi.org/10.1121/1.3651790
9. Bissinger G. Structural acoustics of good and bad violins. J Acoust. 2008;124:1764–1773. https://doi.org/10.1121/1.2956478
10. Meinel H. Regarding sound quality of violins and a scientific basis for violin construction. J Acoust. 1957;29:817–822. https://doi.org/10.1121/1.1909064
11. Gabrielsson A, Jansson EV. Long-time-average-spectra and rated qualities of twenty-two violins. Acustica. 1979;42(1):47–55.
12. Jansson EV. Admittance measurements of 25 high quality violins. Acta Acoust. 1997;83:337–341.
13. Dünnwald H. Deduction of objective quality parameters on old and new violins. J Catgut Acoust Soc. 1991;1(7):1–5.
14. Rabiner L, Gold B. Theory and application of digital signal processing. Englewood Cliffs, NJ: Prentice Hall Inc; 1975.