A Comparative Study on Anatomical Characteristics of the Mutations of *Phyllostachys bambusoides*: Ssanggol- and Min-bamboo

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The anatomical characteristics of the culms and culm bases of ssanggol- and min-bamboo, which are mutated species of *Phyllostachys bambusoides*, were investigated using optical microscopy to understand the material properties. The vascular bundles in the culms and culm bases of both species were type I. There were a few abnormal vascular bundles in the culm base of ssanggol-bamboo, and more developed fiber bundles in the inner part of min-bamboo. A wavy surface was observed in the pith cavity of the ssanggol-bamboo culms. In the inner part, the vascular bundles of min-bamboo culms showed a regular diagonal arrangement, whereas those of ssanggol-bamboo were distributed randomly. In the culm base, ssanggol-bamboo had a significantly higher proportion of parenchyma and vessels, whereas min-bamboo had a higher fiber proportion. Both species had comparable proportions of cells in their culms. The vascular bundle density of min-bamboo was significantly higher than that of ssanggol-bamboo, whereas ssanggol-bamboo showed a significantly larger vessel diameter than min-bamboo. Ssanggol-bamboo had a shorter parenchyma cell length and larger parenchyma cell width than min-bamboo, whereas the min-bamboo culm showed a longer fiber length than that of ssanggol-bamboo. Furthermore, in the culm base, the fibers of ssanggol-bamboo were longer.

DOI: 10.15376/biores.18.2.3228-3243

Keywords: Min-bamboo; Phyllostachys bambusoides; Qualitative and quantitative anatomical characteristics; Ssanggol-bamboo

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INTRODUCTION

Bamboo grows in the southern part of the Korean peninsula. It is a source of medicine, food, building material, pulp paper, and material for crafts and musical instruments (Kang and Lee 2011).

Korean traditional musical instruments include a wide range of types such as string, wind, and percussion. Among the traditional Korean musical instruments, daegeum, known as the large bamboo flute, has been used as an important primary instrument in traditional concerts because it creates the most authentic Korean sound. Moreover, the fascinating sound from traditional bamboo instruments such as Daegeum is well-received by all.

Ssanggol-bamboo, a mutated species of *Phyllostachys bambusoides*, has been used as the most suitable material for manufacturing Daegeum because of its thick bamboo culm and hardness (Kang and Lee 2011; Kim *et al.* 2018). Min bamboo is also a mutated species of *P. bambusoides* and is sometimes used as raw material for daegeum. However, there is no study regarding the quality of both bamboos to support the effective utilization of both bamboos for daegeum.

There have been a few studies regarding the acoustical properties of *Phyllostachys* bamboo. Kang and Lee (2011) reported that the ultrasonic properties of *Phyllostachys bambusoides* were different from wood because of the distinctive anatomical structure of bamboo tissue, and the ultrasonic velocity of the peripheral zone was higher than the inner zone. Deng *et al.* (2022) mentioned that the outer part of *Phyllostachys pubescens* showed higher acoustical converting efficiency than the inner part owing to a lower hemicellulose content, number of parenchyma cells, and porosity.

A few studies on the anatomical characteristics of Korean bamboo species have been conducted by Lee and Park (1987), So *et al*. (1999), Yoon (2010), and Jeon *et al*. (2018a, b). Lee and Park (1987) investigated the anatomical characteristics of culm, as well as the dimensional variation in the length of internodes and culm thickness in *P. bambusoides*, *Phyllostachys edulis*, *Phyllostachys nigra* var. *henonis*, and *Phyllostachys nigra* grown in Damyang district. So *et al*. (1999) observed the anatomical characteristics of the surfaces of *P. bambusoides, P. nigra* var. *henonis,* and *Phyllostachys pubescens* grown in Damyang district. The vascular bundles of all species were type I with reticulate vessels and tyloses (Lee and Park 1987; So *et al*. 1999). Yoon (2010) investigated the anatomical characteristics of 20-day-olds, 60-day-olds, 1-year-old, and 2-year-old moso bamboo (*P. pubescens*). Yoon (2010) reported that the vascular bundle sheath was completely formed in 60-day-old bamboo. Meanwhile, all tissues were completely formed and mature in 1-year-old bamboo. Jeon *et al*. (2018a) investigated the anatomical characteristics of three Korean bamboo species: *P. pubescens*, *P. nigra*, and *P. bambusoides*. The three Korean bamboo species had vascular bundle type I with tyloses in the intercellular space. Furthermore, the relative crystallinity and crystal width of *P. bambusoides* were the highest among the three species. Jeon *et al*. (2018b) reported significant differences in the qualitative and quantitative anatomical characteristics between moso bamboo samples that were 1-year-old and 2-year-old, or older. They confirmed that the size of the vascular bundle sheath, fiber length, and relative crystallinity had the lowest values in 1-year-old bamboo, and the quantitative anatomical characteristics between 2-year-old and 5-year-old bamboo were not significantly different.

To date, there has been no comparative study of the anatomical characteristics of ssanggol- and min-bamboo. To understand the material characteristics of both bamboo species, for their use as musical instruments, the qualitative and quantitative anatomical characteristics of the culms and culm bases were observed.

EXPERIMENTAL

Materials

Nine culms with 5 to 7 m height from each 4 to 5 years old ssanggol-bamboo and min-bamboo were harvested from Jangheung (34°80′ N, 126°83′ E) and Gimhae (35°32′ N, 128°80′ E), respectively, in Korea. The air-dried bamboo samples were divided into culm bases and culms (Fig. 1). Anatomical characteristics of the bamboo culm were observed in the third internode, which was approximately 20 cm above the ground. In the present study, the 3rd internode was used because the length of the internode is mostly constant from the 3rd internode of both bamboo species. The bamboo culm and culm base were divided into inner and outer part. The basic information for each sample is shown in Table 1 and Fig. 2.

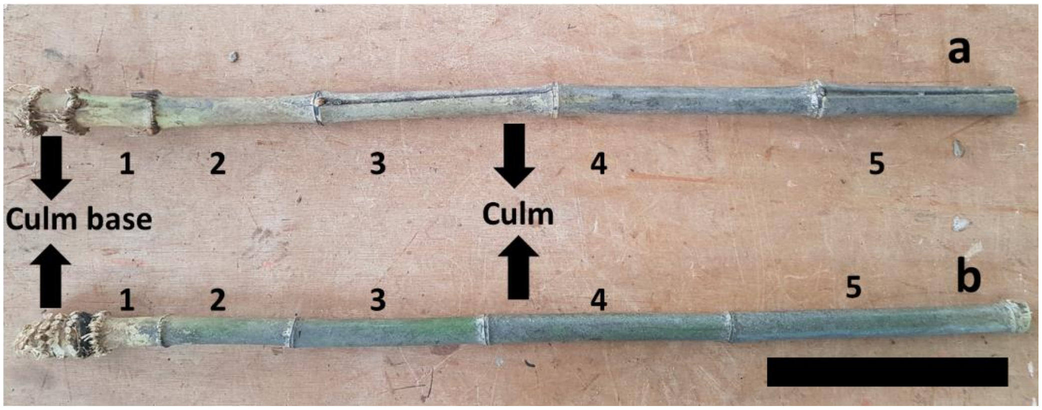

Fig. 1. Culm and culm base of ssanggol- (a) and min-bamboo (b) used in this study (Fig. 1A). Black scale bar: 20 cm

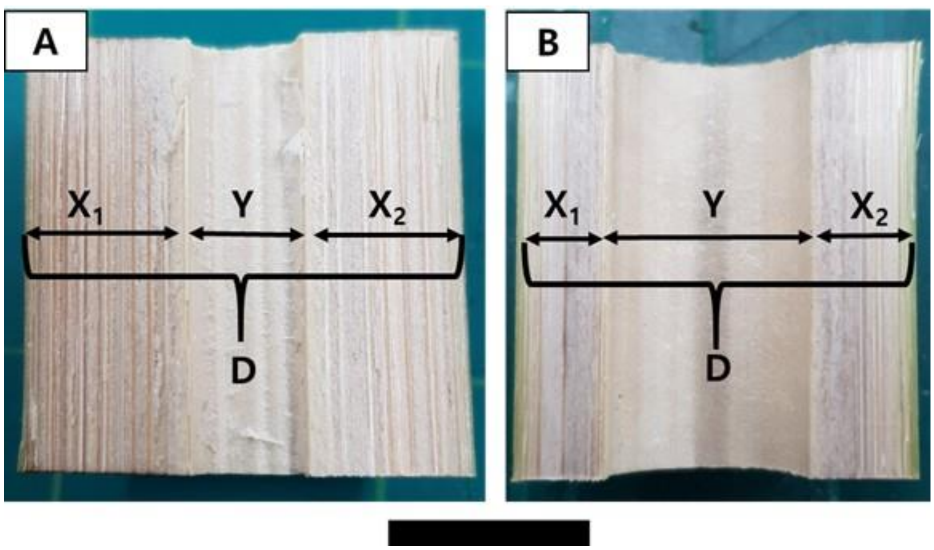

Fig. 2. Split bamboo culm of ssanggol- (A) and min-bamboo (B). X: culm thickness, Y: pith cavity, D: culm diameter. Black scale bar: 10 mm

Table 1. Basic Information on Bamboo Samples

	Number of Culms	Thickness (mm)				Culm Ratio (%)*	Internode Length (mm)
		X_1	X_2	Y	D		
Ssanggol -bamboo	9	8.4 (±0.2)	8.3 (±0.2)	5.9 (±0.2)	22.6 (±0.4)	74.1 (±0.4)	189 (±15)
Min -bamboo		4.7 (±0.1)	4.9 (±0.1)	9.5 (±0.4)	19.1 (±0.3)	50.3 (±1.3)	142 (±11)

Note: the number in the parentheses is the standard deviation value.
*Culm ratio is the ratio of the total culm thickness (X_1+X_2) to pith cavity diameter (Y).

Optical Microscopy

Specimens with dimensions of 15 mm (*L*) × 4 to 9 mm (*R*) × 10 mm (*T*) from the inner and outer part of the bamboo culm and culm base were prepared. The transverse, radial, and tangential sections were observed using these specimens. The samples were soaked in a boiling mixture of glycerin and water (1:1). Thereafter, the three surfaces were sliced to a thickness of 15 to 20 µm using a sliding microtome (MSL-H, NOW, Tokyo, Japan). The slices were stained with each 1% (v/v) safranin and light green diluted in 99% ethanol and dehydrated with a series of alcohol (50%, 70%, 90%, 95%, and 99% ethanol) and xylene solutions (50%, 100% xylene) (Park *et al.* 1993). The permanent slides were prepared using Canada balsam. The qualitative and quantitative anatomical characteristics were observed under an optical microscope (Nikon ECLIPSE, E600, Tokyo, Japan) connected to an image analysis system (IMT i-Solution Lite, Vancouver, Canada).

In the present study, the vascular bundle was identified according to Grosser and Liese (1971). The authors classified the basic vascular bundle types of bamboo into 4 types. Types I and II show a central vascular strand (vessels, phloem, and an intercellular space) with supporting tissue as a fiber bundle. The fiber bundle at intercellular space is bigger in type II than in type I. Tyloses are observed in the intercellular space of type I, while those are absent in type II. Type III shows a central vascular strand and a fiber strand, whereas type IV has a central vascular strand and two fiber strands.

The percentage of cell types on the cross-section was determined to be the proportion of the area of each cell type, such as parenchyma, vessel (vessel, phloem, and intercellular spaces), and parenchyma, to the total area of 4 mm^2, using optical micrographs at 4x magnification (Maulana *et al.* 2022). The cell proportion on the cross-section was examined in 10 areas of 4 mm^2 using the inner part of the bamboo culm and culm base. The vascular bundle density was the number of vascular bundles per 4 mm^2 and the measurement was performed in 40 areas of 4 mm^2 on the cross-section. The tangential vessel diameter on the cross-section was measured in 50 vessels. The parenchyma cell dimensions on the radial surface, such as length and width, were measured in 50 cells.

For the fiber length, specimens with dimensions of 1 mm wide and 20 to 30 mm long in the longitudinal direction were prepared near the pith cavity and near the epidermis of the bamboo culm and culm base. The specimens were immersed in Schultze's solution for 24 h and then heated at 70 °C for 48 h. This was performed using a heating block while stirring at 2-hour intervals (Park *et al.* 1993). The samples were washed with distilled water until they were neutralized, and the fiber length was measured from 50 fibers.

Statistical Analysis

The significant differences in the quantitative anatomical characteristics between species, and between culm and culm base were statistically examined using analysis of variance (ANOVA) and post-hoc Duncan's multiple range tests. The statistical analyses were performed using SPSS software (SPSS ver. 24, IBM Corp., Armonk, NY, USA).

RESULTS AND DISCUSSION

Qualitative Anatomical Characteristics

Macroscopic structure of the culm and culm base

The longitudinal surfaces of the bamboo culms and the transverse surface of the bamboo culm and culm base are presented in Figs. 3 and 4, respectively. Ssanggol-bamboo has two types of sulci along the direction of the axis on its surface one deep and one shallow. A base of branch commonly occurred between those sulci in ssanggol-bamboo culm and culm base. In contrast, min-bamboo only has a shallow sulcus on its culm surface showing repetition in 180° rotations for each internode, which commonly occurred next to the base of a branch in the culm. Sulci were absent in the culm base of min-bamboo. McClure (1945) and Renvoize (1995) mentioned that a shallow groove or sulcus from base to the tip of the internode in *Phyllostachys aureosulcata* and *Phyllostachys aurea* commonly occurred above branching nodes.

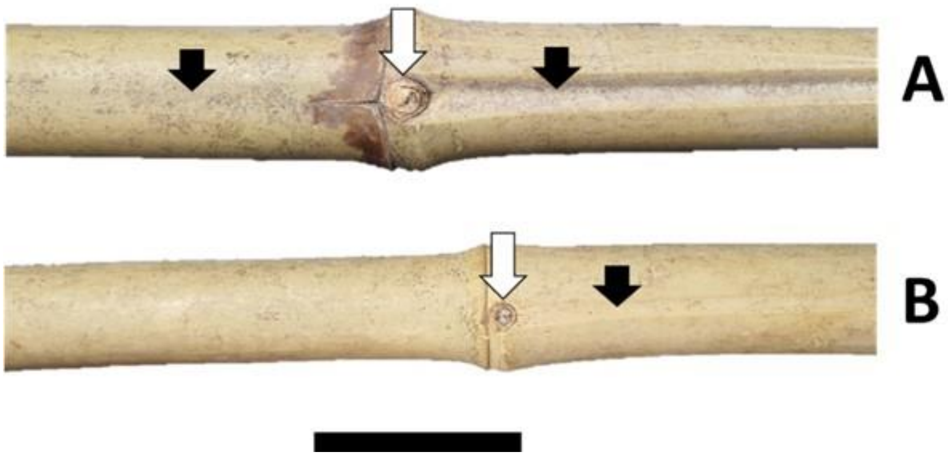

Fig. 3. Culm of ssanggol- (A) and min-bamboo (B) with sulci (black arrow) on the internode and base of a branch in the node (white arrow). Black scale bar: 4 cm

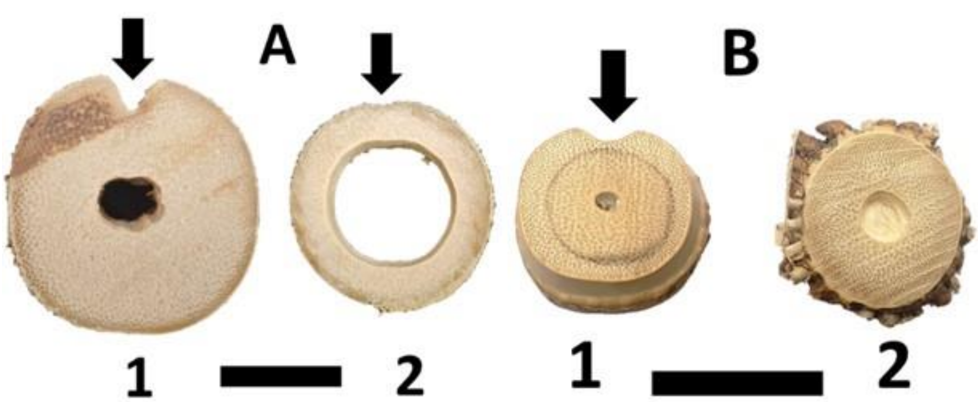

Fig. 4. Transverse surface of culm (A) and culm base (B) of ssanggol- (1) and min-bamboo (2). The black arrows point to the sulci. Black scale bar in A and B: 1.5 cm and 2.5 cm, respectively.

Cell structure and arrangement on the three surfaces

Optical micrographs of the cross-section in the culm base and culm of ssanggol- and min-bamboo are shown in Fig. 6. There were different distances from the epidermis to the vascular bundles between the culm base and culm in both species. The distance from the epidermis to the outermost vascular bundles was 500 to 1,000 μm, whereas, in the culm, the distance was less than 100 μm.

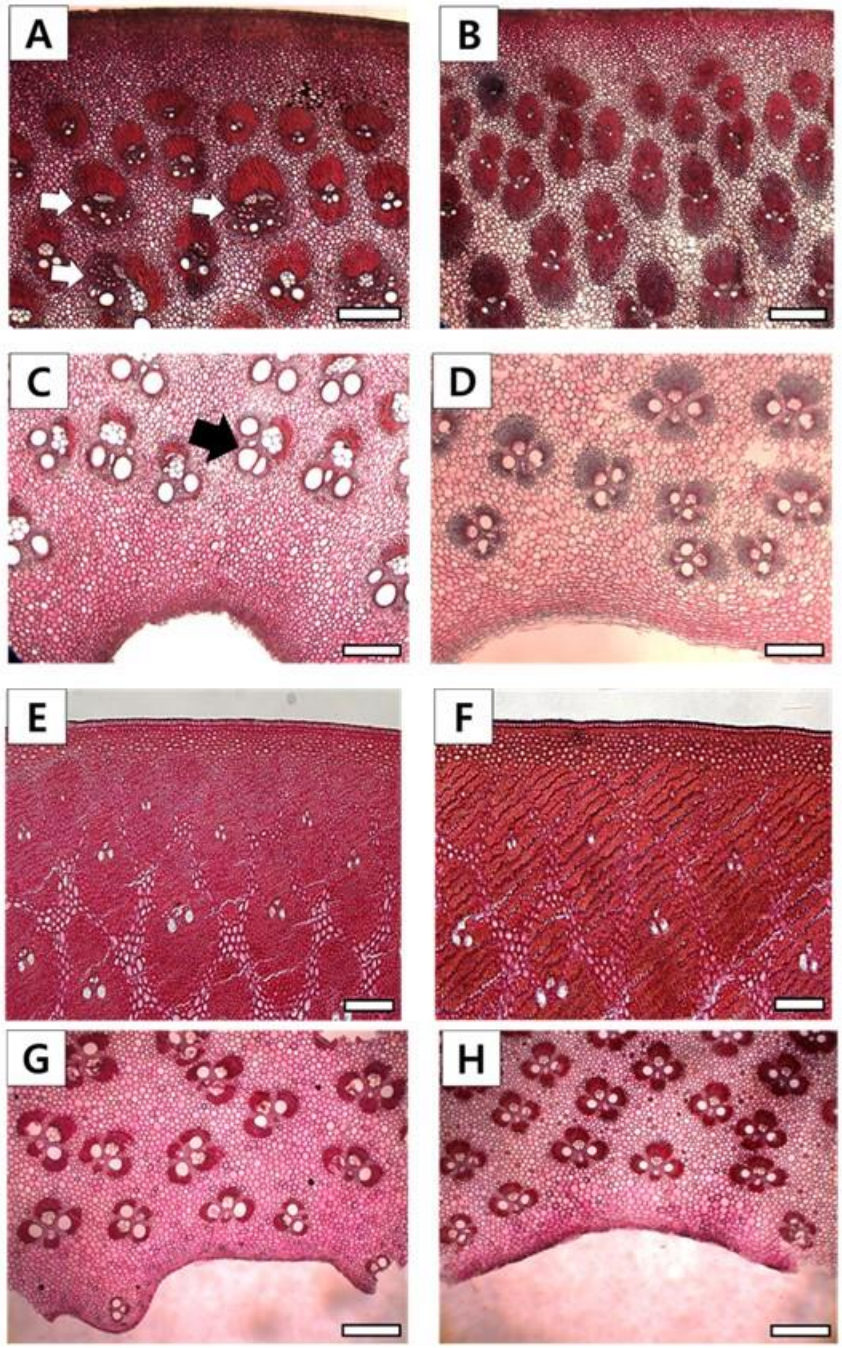

Fig. 5. Optical micrographs of the cross-section of ssanggol- (A, C, E, and G) and min-bamboo (B, D, F, and H). Outer (A, B) and inner (C, D) part of the culm base. Outer (E, F) and inner (G, H) part of culm. White arrows indicate abnormal vascular bundles. Black arrow indicates multiple metaxylem vessels. Scale bars for A, B, C, D, G, and H: 500 µm. Scale bars for E and F: 200 µm

In the outer part of the culm base, ssanggol-bamboo showed type I vascular bundles, but there were more or less different shapes (white arrows in Fig. 5A) of type I vascular bundles compared with those of min-bamboo. Min-bamboo mainly showed normal type I vascular bundles. In the inner part of the culm base, both species showed type I vascular bundles, which were randomly arranged.

The pith cavity of the ssanggol-bamboo culms had a wavy surface, whereas the min-bamboo had a flat pith cavity surface (Figs. 5 G and H). In the inner part of the bamboo culm, the vascular bundle of the min-bamboo showed a more regular diagonal arrangement than that of the ssanggol-bamboo. It was also observed that the vascular bundle was smaller and denser in the outer part than in the inner part of both species. The typical type I vascular bundle in ssanggol- and min-bamboo culms are shown in Fig. 6, which consisted of vessels, phloem with thin-walled sieve tube, intercellular space with tyloses, and fiber bundles.

Grosser and Liese (1971) observed 52 bamboo species of 14 genera distributed throughout Asia and reported that the vascular bundles became denser toward the epidermis in all species. Additionally, vascular bundle type I is commonly observed in *Phyllostachys* bamboo, which is in line with the results of the present study. Ito *et al.* (2015) reported that the distance between the vascular bundles became narrower toward the epidermis of rhizomes, culms, and roots of *P. pubescens*, which is consistent with the results of this study. Therefore, it is considered that the number of vascular bundles generally increases toward the epidermis, and the vascular bundles also become dense, regardless of the bamboo species. The vascular bundle types of both species in this study were consistent with those found in *P. bambusoides*, *P. nigra*, and *P. pubescens* (So *et al.* 1999; Jeon *et al.* 2018a).

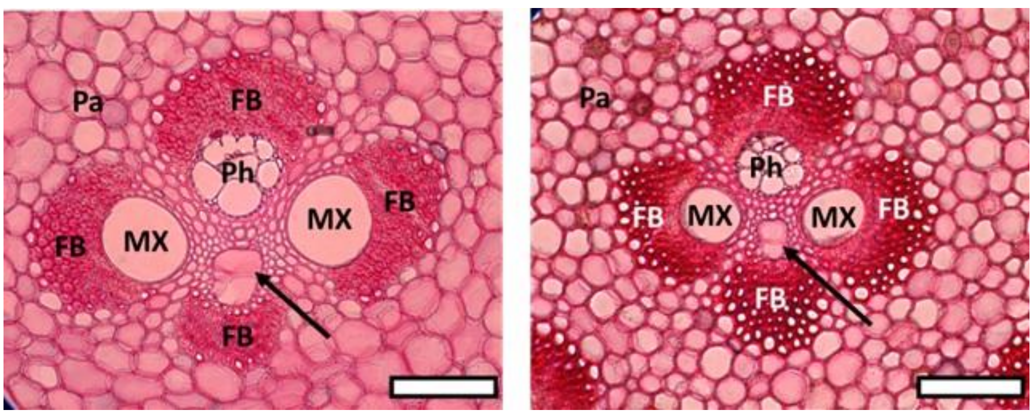

Fig. 6. Optical micrographs of typical type I vascular bundles on cross-sections of ssanggol- (left) and min-bamboo (right) culm. FB: fiber bundle, MX: metaxylem vessel, Ph: phloem with thin-walled sieve tube, Pa: parenchyma cells. The black arrows indicate intercellular space with tyloses. Scale bars: 100 µm

Optical micrographs of the radial and tangential surfaces in the culm base and culm of ssanggol- and min-bamboo are shown in Figs. 7 and 8, respectively.

In the outer part of the radial and tangential surfaces, the culm base of ssanggol-bamboo mainly presented a small square shape for the parenchyma cells, while those of min-bamboo showed a small square shape and a rectangular shape. In the inner part, the culm bases of both species showed square-shaped parenchyma cells. Additionally, in the radial section of both species, the parenchyma cells tended to be smaller toward the pith and epidermis area and had a dense distribution.

In the outer part of the bamboo culm, the parenchyma cells of both species were rectangular and had a regular arrangement in the axial direction. In the inner part of the culm, the parenchyma cells of both species had square and rectangular shapes. In the radial section of both species, the parenchyma cells became smaller toward the pith and epidermis area and showed a compact distribution. Additionally, tyloses were observed in the intercellular spaces of both species (Figs. 7G and H).

The shape of the parenchyma cells on the tangential section of both species was comparable to that on the radial surface, which is in line with the results of Jeon *et al*. (2018a,b). The authors reported that the tangential surfaces of *P. pubescens, P. nigra*, and *P. bambusoides* had anatomical characteristics that were similar to those of the radial surface. Markedly, the radial and tangential surfaces of *P. pubescens* showed a small and circular shape for the parenchyma cells (Jeon *et al*. 2018b). Grosser and Liese (1971) also reported that elongated and almost cube-like parenchyma cell shapes were mainly observed on the radial surface of 52 bamboo species.

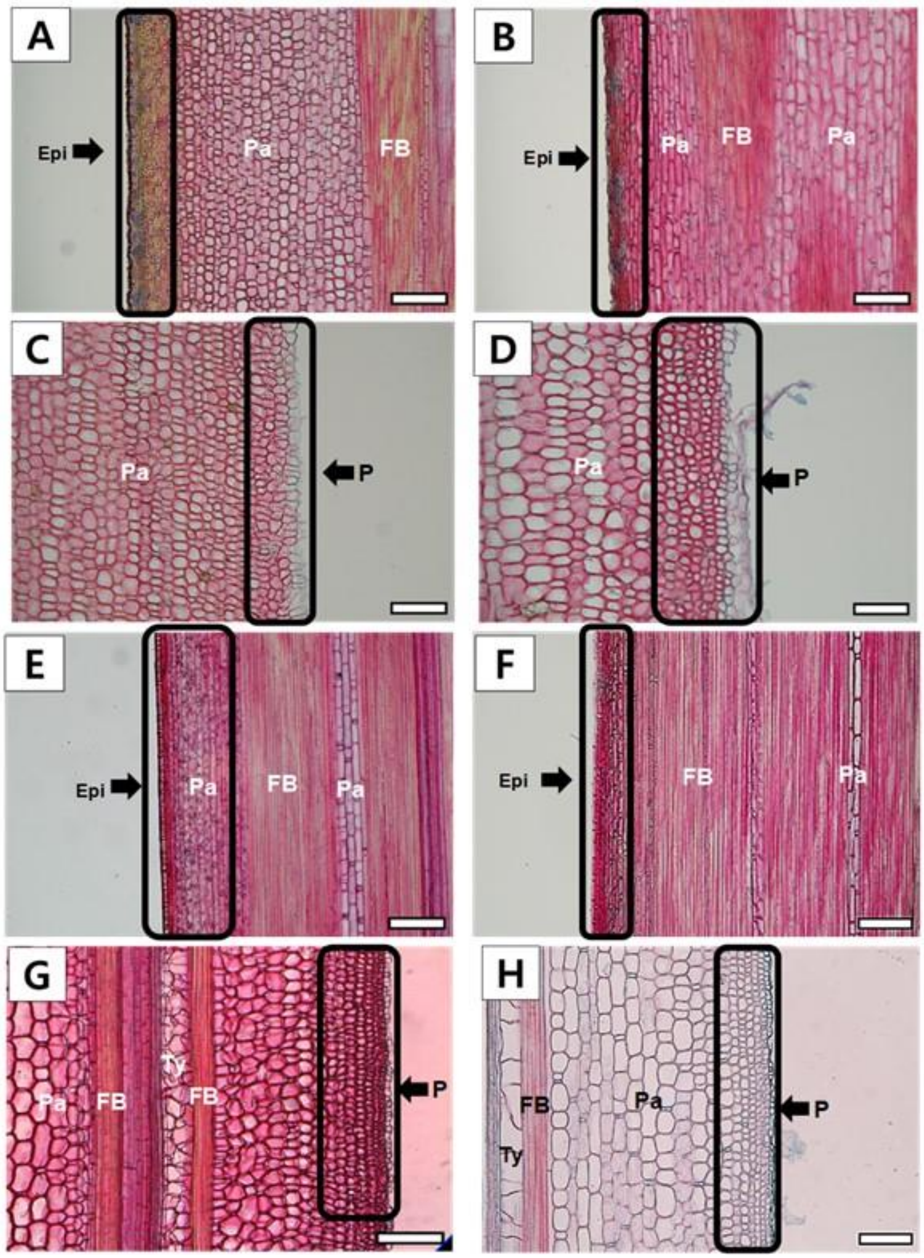

Fig. 7. Optical micrographs of the radial section in ssanggol- (A, C, E, and G) and min-bamboo (B, D, F, and H). Outer (A, B) and inner (C, D) part of culm base. Outer (E, F) and inner (G, H) part of culm. Epi: epidermis area, P: pith area, FB: fiber bundle, Pa: parenchyma cells. Scale bars: 200 µm

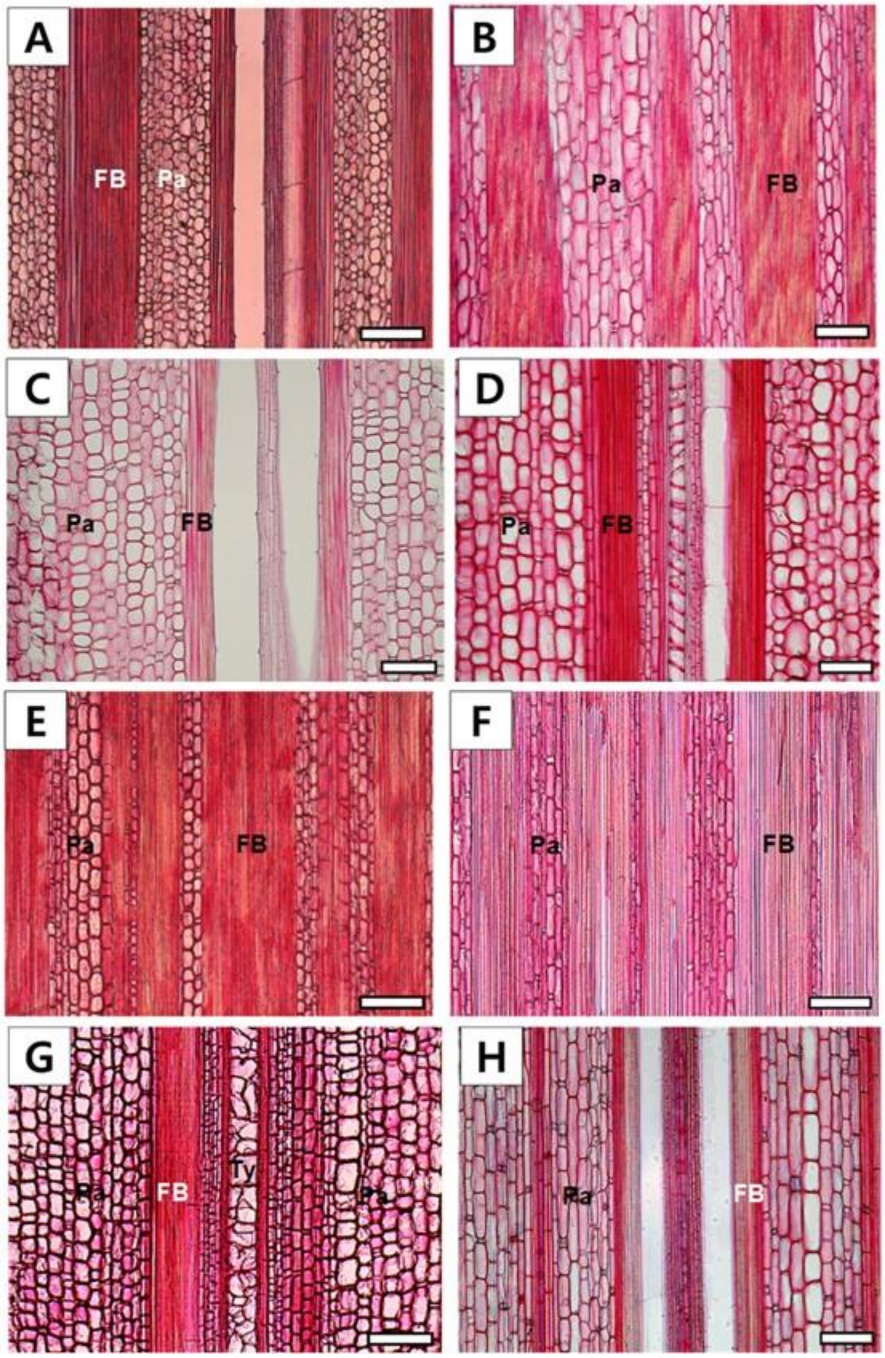

Fig. 8. Optical micrographs of the tangential section of ssanggol- and min-bamboo. Outer (A, B) and inner (C, D) part of culm base. Outer (E, F) and inner (G, H) part of culm. FB: fiber bundle, Pa: parenchyma cells, Ty: tyloses. Scale bars: 200 µm

Quantitative Anatomical Characteristics

Cell proportion

Table 2 shows the cell proportion in the culm base and culm of ssanggol- and min-bamboo. In culm base, the percentage of parenchyma cells and vessels in ssanggol-bamboo was significantly higher than that in min-bamboo, and ssanggol-bamboo had a significantly lower proportion of fiber than min-bamboo. There was no significant difference in the parenchyma and fiber percentage of the culm between the two species, while ssanggol bamboo culm had a significantly higher vessel proportion than min bamboo culm. In both species, the proportion of parenchymal cells was higher in the culm than in the culm base, whereas the percentage of vessels and fibers was higher in the culm base than in the culm. As mentioned by Darwis *et al.* (2020), *Gigantochloa pruriens* consisted of 64.3 to 74.5% vascular bundles and 25.5 to 35.7% parenchyma cells. Maulana *et al*. (2022) reported that the cell proportion in *Bambusa* species was 60 to 63% parenchyma, 23 to 27% fiber, and 11 to 13% vessels; while in *Dendrocalamus* species, the proportion was 68 to 72% parenchyma, 23% fiber, and 5 to 9% vessels. Ssanggol- and min-bamboo had higher proportions of parenchyma and vessels than the *Bambusa* and *Dendrocalamus* species reported by Maulana *et al*. (2022).

It seems like the cell proportion of bamboo affects the acoustical properties. The ultrasonic velocity decreased from the outer part to the inner part of *Phyllostachys bambusoides* culm (Kang and Lee 2011). Iswanto *et al.* (2020) mentioned that the material with much porous space showed greater sound absorption. In contrast, the greater board density value had a lower sound absorption coefficient value. Furthermore, Deng *et al.* (2022) mentioned that *Phyllostachys pubescens* showed higher acoustical converting efficiency in the outer part than the inner part owing to a lower hemicellulose content, number of parenchyma cells, and porosity. Further study regarding the acoustical properties of both bamboo species is needed.

Table 2. Cell Proportion within Ssanggol- and Min-bamboo (unit: %)

	Ssanggol-bamboo	Min-bamboo
Culm base		
- Parenchyma	66 ± 5.1^{bA}	62 ± 6.4^{aA}
- Vessels	8 ± 2.8^{bB}	5 ± 1.6^{aB}
- Fiber	26 ± 4.9^{aB}	33 ± 5.6^{bB}
Culm		
- Parenchyma	75 ± 4.1^{aB}	72 ± 4.4^{aB}
- Vessels	4 ± 0.8^{bA}	3 ± 0.3^{aA}
- Fiber	21 ± 4.1^{aA}	24 ± 4.3^{aA}

Note: The numbers in the same row followed by the same lowercase letters are insignificant at the 5% significance level between species. The mean value in the same column followed by the same capital letters is insignificant at the 5% significance level between the culm and culm bases.

Vascular bundle density

The vascular bundle densities in the culm base and culm of ssanggol- and min-bamboo are shown in Table 3. The vascular bundle density in both the culm and culm bases of min-bamboo was significantly higher than that of ssanggol-bamboo. In the culm and culm bases of both species, the vascular bundle density of the inner part was considerably lower than that of the outer part. Furthermore, the vascular bundle density in bamboo culms was significantly higher than that in the culm base. Huang *et al*. (2015) reported a significant decrease in the vascular bundle frequency of *Bambusa rigida* from the outer zone to the inner zone. Additionally, the vascular bundle density of *P. pubescens*, *G. pruriens*, *Gigantochloa pseudoarundinacea*, *Gigantochloa apus*, and *Gigantochloa atroviolacea* was higher in the outer part than inner part (Jeon *et al*. 2018b; Darwis *et al.* 2020; Maulana *et al*. 2021).

Table 3. Vascular Bundle Density of Ssanggol- and Min-bamboo (Unit: number/4 mm^2)

	Ssanggol-bamboo	Min-bamboo
Culm base		
- Inner	4.9±1.1^{aA}	4.8±0.9^{aA}
- Outer	6.3±1.2^{aA}	9.5±2.9^{bA}
- Average	5.6±1.4^{aA}	7.1±3.2^{bA}
Culm		
- Inner	4.6±1.0^{aA}	11.0±1.8^{bB}
- Outer	12.3±1.2^{aB}	21.6±3.2^{bB}
- Average	8.6±3.9^{aB}	16.3±5.9^{bB}

Note: The numbers in the same line followed by the same lowercase letters are insignificant at the 5% significance level between species. The mean value in the same column followed by the same capital letters is insignificant at the 5% significance level between the culm and culm bases.

Vessel diameter

Table 4 shows the vessel diameters in the culm base and culm of ssanggol- and min-bamboo. In both the culm and culm bases, the vessel diameter of ssanggol-bamboo was significantly larger than that of min-bamboo. Moreover, the vessel diameter in the inner part was larger than that in the outer part. Vessels in the culm bases of both species had significantly larger diameters than those in the bamboo culms. Lee and Park (1987) reported that the diameter of the vessel slightly decreased toward the epidermis in four species of *Phyllostachys*. Hisham *et al*. (2006) and Wang *et al*. (2011) also reported that the vessel diameter of *Gigantochloa scortechinii* and *Fargesia yunnanensis* decreased from the pith cavity to the epidermis. As reported by Darwis *et al.* (2020), the vessel diameter of *G. pruriens* decreases from the outer part toward the inner part of the bamboo culm.

Table 4. Vessel Diameter of Ssanggol- and Min-bamboo (unit: μm)

Characteristics	Ssanggol-bamboo	Min-bamboo
Culm base		
- Inner	163.5±18.3^{bB}	115.7±20.7^{aB}
- Outer	81.9±12.4^{bB}	60.3±23.7^{aA}
- Average	120.7±53.1^{bB}	86.8±35.5^{aB}
Culm		
- Inner	126.0±16.5^{bA}	88.2±14.7^{aA}
- Outer	71.2±17.6^{bA}	54.5±10.8^{aA}
- Average	100.6±34.0^{bA}	73.8±20.9^{aA}

Note: The numbers in the same line followed by the same lowercase letters are insignificant at the 5% significance level between species. The mean value in the same column followed by the same capital letters is insignificant at the 5% significance level between the culm and culm bases.

Dimensions of the parenchyma cell

Table 5 shows the parenchyma cell dimensions in the culm base and culm of ssanggol- and min-bamboo. In the culm base, min bamboo showed a significantly greater parenchyma cell length than ssanggol-bamboo. Moreover, the parenchyma cell length in the inner part of both species was shorter than that in the outer part. In bamboo culm, notably, the ssanggol-bamboo had a significantly shorter parenchyma cell length than the min-bamboo. The parenchyma cell length of both species was shorter in the outer part than in the inner part. The culm of both species had significantly greater parenchyma cell length than the culm base. Similarly to this study, Jeon *et al*. (2018a) reported that the parenchyma cell length in the inner part of the *P. pubescens, P. nigra*, and *P. bambusoides* culms was 107.5 µm, 100.2 µm, and 104.5 µm, respectively. Maulana *et al*. (2021) mentioned that the parenchyma cell length of the *G. pseudoarundinacea*, *G. apus*, and *G. atroviolacea* culms were 101.4µm, 78.1µm, and 120.4 µm, respectively. Thereafter, Maulana *et al*. (2022) found that the parenchyma cell length in the outer part of the culms of *Dendrocalamus asper, Dendrocalamus giganteus, Bambusa vulgaris* var. *vulgaris*, and *Bambusa vulgaris* var. *striate* was 98.1 µm, 86.1 µm, 188.7 µm, and 82.1 µm, respectively.

Table 5. Parenchyma Cell Dimensions of Ssanggol- and Min-bamboo (unit: µm)

Characteristics	Ssanggol-bamboo	Min-bamboo
Parenchyma Length		
Culm base		
- Inner	41.8±14.0^{aA}	77.3±32.2^{bA}
- Outer	50.4±10.9^{aA}	93.1±30.7^{bA}
- Average	46.1±13.2^{aA}	85.2±32.3^{bA}
Culm		
- Inner	104.6±27.5^{aB}	131.8±50.2^{bB}
- Outer	95.5±29.5^{aB}	100.0±30.2^{aA}
- Average	100.0±28.8^{aB}	115.9±44.2^{bB}
Parenchyma Width		
Culm base		
- Inner	55.1±11.3^{bA}	39.3±10.0^{aA}
- Outer	28.5±6.0^{aA}	33.3±9.1^{bA}
- Average	41.8±16.1^{bA}	36.4±9.9^{aA}
Culm		
- Inner	54.3±18.2^{bA}	44.8±12.2^{aA}
- Outer	39.7±7.8^{aB}	37.8±4.5^{aA}
- Average	47.0±15.8^{bA}	41.1±9.8^{aA}

Note: The numbers in the same line followed by the same lowercase letters are insignificant at the 5% significance level between species. The mean value in the same column followed by the same capital letters is insignificant at the 5% significance level between the culm and culm bases.

In the inner part of the culm base, ssanggol-bamboo had significantly larger parenchyma width than min bamboo, while in outer part, the parenchyma was significantly larger in min-bamboo than ssanggol-bamboo. In the bamboo culm, the parenchyma cell width of ssanggol-bamboo was significantly larger than those of min-bamboo. Furthermore, the parenchyma cell width was smaller in the culm base than in the culm, but this difference was not significant. The parenchyma cell widths in the culm base and culm of both species were smaller in outer part than in inner part. Jeon *et al*. (2018a) mentioned that the parenchyma cell widths of *P. pubescens, P. nigra,* and *P. bambusoides* culms were 45.6 µm, 34.4 µm, and 44.1 µm, respectively. In addition, as reported by Jeon *et al*. (2018b), the parenchyma cell width of the culm of *P. pubescens* was 56.1µm.

Fiber length

Optical micrographs of the fibers in the culm base and culm of ssanggol- and min-bamboo are shown in Fig. 9. The micrographs showed that the fibers in the culm were longer than those in the culm base.

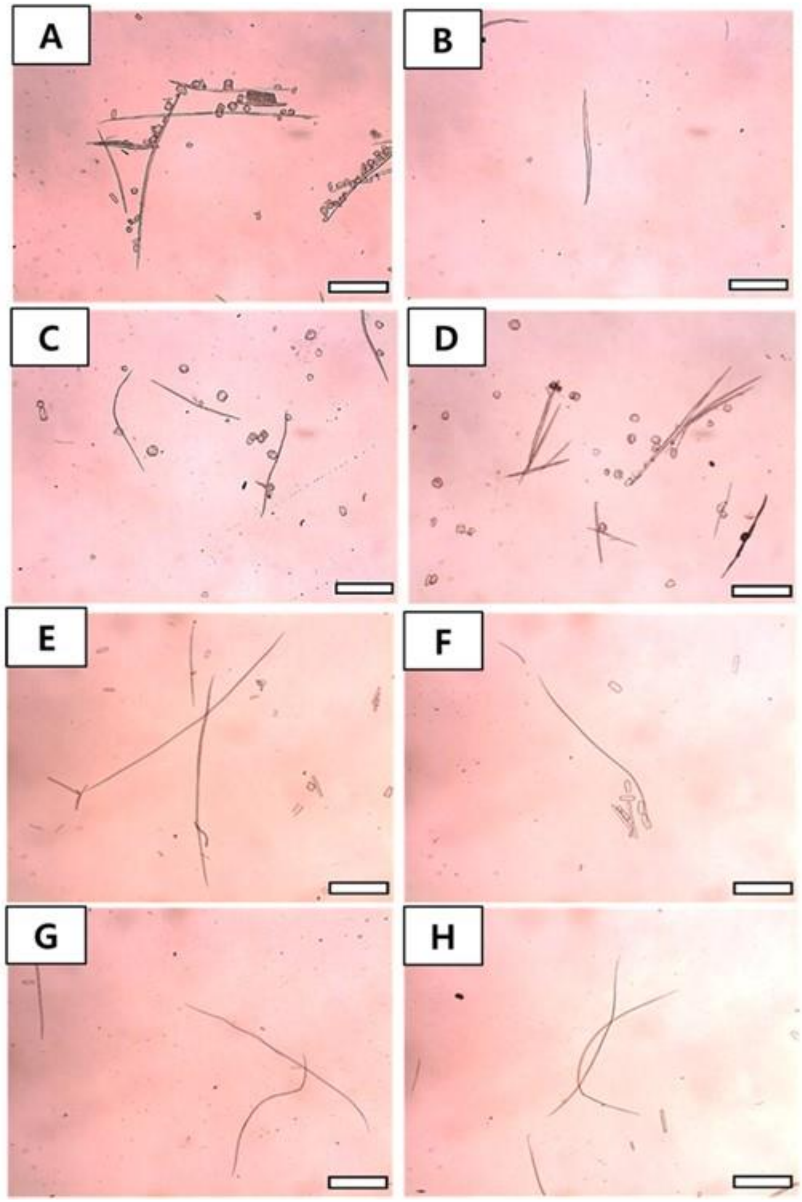

Fig. 9. Optical micrographs of the fibers in ssanggol- (A, C, E, and G) and min-bamboo (B, D, F, and H). Outer (A, B) and inner (C, D) parts of the culm base. Outer (E, F) and inner (G, H) parts of the culm. Scale bars: 500 µm

Table 6 shows the fiber length in the culm and culm bases of ssanggol- and min-bamboo. In the culm base, the fiber length of ssanggol-bamboo was significantly longer than that of min-bamboo. Furthermore, the fiber length was longer in the outer part than in the inner part of both species. In bamboo culms, the fiber length of min-bamboo was longer than that of ssanggol-bamboo. The fiber length of ssanggol-bamboo was longer in the inner part than the outer part, whereas min-bamboo showed comparable fiber lengths between the inner and outer parts. In the present study, the fiber length in the culm of both species was longer than that of the culm base. Liese (1998) the fiber dimension increased from peripheral layer inwards to the outer third of the culm wall and decreased again towards the inner wall. Jeon *et al*. (2018a) reported that the fiber length of the culm in *P. bambusoides* was 2239.3 µm near the pith cavity and 2033.5 µm near the epidermis, which is similar to the fiber length of min-bamboo in the present study. The fiber length of *Phyllostachys pubescens*, *Phyllostachys nigra*, *Phyllostachys bambusoides* bamboo culm was greater in the outer part than the inner part (Jeon *et al*. 2018a; 2018b). According to Maulana *et al*. (2021 and 2022), the fiber length of *Gigantochloa pseudoarundinacea*, *Gigantochloa* apus, *Gigantochloa atroviolacea*, *Dendrocalamus asper*, *Dendrocalamus giganteus*, and *Bambusa vulgaris* increased from pith cavity to epidermis.

Table 6. Fiber Length of Ssanggol- and Min-bamboo (unit: µm)

	Ssanggol-bamboo	Min-bamboo
Culm base		
- Inner	1190.1 ± 193.3^{bA}	894.1 ± 92.3^{aA}
- Outer	1246.6 ± 240.9^{bA}	958.0 ± 109.5^{aA}
- Average	1218.4 ± 219.1^{bA}	926.4 ± 105.8^{aA}
Culm		
- Inner	1986.5 ± 353.7^{aB}	2323.4 ± 618.3^{bB}
- Outer	2220.0 ± 443.2^{aB}	2253.6 ± 361.2^{aB}
- Average	2103.2 ± 401.1^{aB}	2288.5 ± 549.4^{bB}

Note: The numbers in the same line followed by the same lowercase letters are insignificant at the 5% significance level between species. The mean value in the same column followed by the same capital letters is insignificant at the 5% significance level between the culm and culm bases.

CONCLUSIONS

1. The vascular bundles in the culm and culm bases of both species were type I. There were a few abnormal vascular bundles and less-developed bundle sheaths in the culm base of the ssanggol-bamboo.
2. In the culm base, ssanggol-bamboo had a significantly higher proportion of parenchyma and vessels and a lower fiber proportion than min-bamboo. In bamboo culms, ssanggol- and min-bamboo had comparable cell proportions.
3. The vascular bundle density of min-bamboo was significantly higher than that of ssanggol-bamboo in all parts, whereas ssanggol-bamboo had a significantly larger vessel diameter than min-bamboo.
4. Ssanggol-bamboo had a shorter parenchyma cell length and a larger parenchyma cell width than min-bamboo in all parts. Min-bamboo showed longer fiber in the culm and shorter fiber in the culm base than ssanggol-bamboo.
5. In both species, the bamboo culm exhibited a greater proportion of parenchyma cells, as well as greater vascular bundle density, parenchyma cell length, and fiber length than those in the culm base, whereas the culm base showed a higher proportion of vessels and fibers.

In summary, this work revealed distinctively different anatomical characteristics between the two species, and between the culm and culm bases, confirming that the anatomical characteristics of both species can be used for quality evaluation and identification indices to support their use as musical instruments.

ACKNOWLEDGMENTS

This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF), which is funded by the Ministry of Education (No. NRF-2016R1D1A1B01008339 and NRF-2018R1A6A1A03025582), the Science and Technology Support Program through the NRF funded by the Ministry of Science and ICT (No. NRF-2019K1A3A9A01000018 and NRF-2022R1A2C1006470), and R&D Program for Forest Science Technology (Project No. 2021350C10-2323-AC03) provided by the Korea Forest Service (Korea Forestry Promotion Institute). This study was also conducted with the support of the National Gugak Center to study the properties of materials used for musical instruments. In addition to these, this work was also supported by the Kangwon National University. The authors thank Editage (www.editage.co.kr) for English language editing.

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Article submitted: August 23, 2022; Peer review completed: October 1, 2022; Revised version received: February 5, 2023; Accepted: February 6, 2023; Published: March 16, 2023.
DOI: 10.15376/biores.18.2.3228-3243