2016 · 3

pISSN 1017-0715
eISSN 2233-7180

Journal of The Korean Wood Science and Technology

Vol. 44 No. 2 March 2016

CONTENTS - I

KSWST The Korean Society of Wood Science & Technology

J. Korean Wood Sci. Technol. 2016, 44(2): 157~165
pISSN: 1017-0715 eISSN: 2233-7180
http://dx.doi.org/DOI : 10.5658/WOOD.2016.44.2.157

Original Article

Anatomical Characteristics of *Paulownia tomentosa* Root Wood[1]

Yue Qi[2] · Jaehyuk Jang[2,3] · Wahyu Hidayat[2,4] · Aehee Lee[2] · Sehwi Park[2,5] · Seunghwan Lee[2] · Namhun Kim[2,†]

ABSTRACT

This study investigated several anatomical characteristics of *Paulownia tomentosa* roots. The root wood was separated into three parts from stem base (top, middle, and base) at different positions below ground. Qualitative anatomical data suggested that the growth rings in earlywood and latewood were structurally different. Furthermore, the root wood vessels were found having 2 to 3 radial multiples and they were appeared in the form of clusters. In addition, some sheath cells and septate axial parenchyma were observed. Regarding the quantitative anatomical characteristics, vessel and ray numbers per mm^2, as well as ray width and height differed significantly among the top, middle, and base rood wood parts. However, there were no significant differences in vessel diameters, cell wall thickness, and width and length of wood fibers among those parts. The crystallinity of the root top part was slightly higher than that of the middle and base parts. Furthermore, the vessel numbers, ray numbers, and ray width and height in the near pith (NP) area were higher compared to those in the near bark (NB) area. However, the fiber width and fiber length at NP were lower than those at NB. Overall, this study demonstrated some significant differences in the anatomical characteristics of the top, middle, and base parts of root wood from *Paulownia tomentosa*.

Keywords : *Paulownia tomentosa*, root wood, wood anatomy

1. INTRODUCTION

The wood structure of woody plant species is mainly studied on stems (Kim *et al*., 2012; 2013) and branches (Jacobsen *et al*., 2007a; Poorter *et al*., 2010; Qi *et al*., 2014), mostly because of their obvious function in supporting of plant's life. Roots also support important functions in plants. For example, they anchor the plants in the substratum, and facilitate the uptake of water and minerals from the environment. Furthermore, roots are important for the storage of reserves. As a consequence, the root wood structure can significantly affect

1 Date Received January 15, 2016, Date Accepted February 25, 2016
2 College of Forest and Environmental Sciences, Kangwon National University, Chuncheon 24341, Republic of Korea
3 The Institute of Forest Science, Kangwon National University, Chuncheon 24341, Republic of Korea
4 Faculty of Agriculture, Lampung University, Bandar Lampung 35145, Indonesia
5 Faculty of Forestry, Bogor Agricultural University, Bogor 16680, Indonesia
† Corresponding author: Nam-Hun Kim (e-mail: kimnh@kangwon.ac.kr)

the wood quality of the rest of the tree.

A few previous studies have investigated the anatomy of root wood (Patel, 1970; Matsumura and Butterfield, 2001). Schuldt *et al*. (2013) investigated the density, anatomy, and hydraulic properties of root wood of tropical rainforest trees. Furthermore, several studies compared root wood with stem wood or branch wood. Rao *et al*. (1989) claimed that the average vessel tangential diameters, and vessel length of root wood were substantially smaller than those of stem wood. Stokke and Manwiller (1994) showed that for black ash (*Quercus velutina*) the vessel elements, fibers, rays, and axial parenchyma differed among stem, branch, and root woods. In addition, Palhares *et al*. (2007) found that the amount of parenchyma cells and thin-walled fibers differed between root wood and stem wood. Lee and Eom (2011) identified the wood anatomy of yellow-poplar grown in Korea, and compared stem and root wood for their vessel and ray elements, and quantitative anatomical features. Furthermore, Fortunel *et al*. (2014) investigated differences of wood specific gravity and anatomy between branches and roots in 113 Amazonian rainforest wood species. They demonstrated that the fiber properties were the major contributors to wood specific gravity, independent of vessel properties, across branches and small woody root.

In Korea, *Paulownia tomentosa* is a fast-growing tree species, and its wood can be used for high-value applications, such as making Korean traditional musical instruments and furniture. In order to optimally utilize *Paulownia tomantosa* wood as a bioresource, and to gain more knowledge of its wood qualities, the anatomical characteristics of stem, branch, and root wood of this species should be studied. In our previous study (Qi *et al*., 2014), we reported the anatomical and physical properties of branch wood. In this study, we examined the root wood anatomical characteristics, and compared the differences among its top, middle, and base parts.

Table 1. The basic information of sample tree

Sample trees	DBH (cm)	Height (m) above ground
Paulownia tomentosa 1	30.9	15.0
Paulownia tomentosa 2	31.2	14.5

2. MATERIALS and METHODS

2.1. Materials

The eleven and thirteen years old *Paulownia tomentosa* trees were obtained from research forest (N 37°51′/E 127°48′) of Kangwon national university in South Korea (Table 1). The experimental samples for investigating anatomical properties were cut from root parts of *Paulownia tomentosa* trees (Fig. 1). The rooting depth of the studied root wood was approximately 2.0 m. Therefore, samples were collected as follows: the root top part consisted of root wood with a diameter of 17.5 cm and was sampled 0.5 m below ground; the middle part with a diameter of 12 cm and was sampled between 0.5 m and 1.0 m below ground; the base part had a diameter of 8.5 cm and was sampled between 1.0 and 1.5 m below ground.

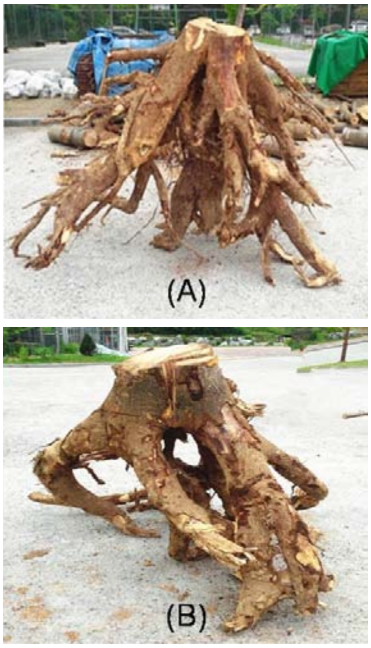

Fig. 1. The samples: (A) the root obtained from No.1 sample tree with the age of eleven years old; (B) the root obtained from No.2 sample tree with the age of thirteen years old.

The obtained root were separated into near pith (NP) and near bark (NB) parts before analyzing their anatomical properties.

2.2. Anatomical characteristics

The blocks of NP and NB root wood were obtained from wood discs. Fifteen-micrometer-thick slices were cut from per root parts by using a sliding microtome (Nippon Optical works, Japan). These sections were stained with Safranin-Astra blue (Von, 1973; Lillie, 1977; Jourez *et al*., 2001), dehydrated in a graded series of alcohol (50%, 70%, 90%, 95%, and 99%), mounted using Canada balsam, and observed under an optical microscope (Nikon Eclipse E600, Japan). The anatomical characteristics, such as number and diameter of vessels, height and width of rays, fiber length, and structure were determined according to the IAWA hardwood feature list (IAWA Committee, 1989) using Total Imaging Solution software (IMT, I-solution Lite, USA). For each characteristic, fifty random measurements were made to determine a mean value.

2.3. Crystalline characteristics

An X-ray diffractometer (Rigaku DMAX2100V, Japan) equipped with a Cu target was used for measuring the crystalline properties, at 40 kV and 40 mA. The root wood relative crystallinity (%) and crystallite width (mm) were calculated by Segal's equation (Segal *et al*., 1959) and Scherrer's equations (Alexander *et al*., 1969), respectively.

2.4. Statistical analysis

Differences in the quantitative features among the root wood top, middle, and base were statistically examined with one-way ANOVA, and post-hoc Duncan's tests (IBM SPSS ver. 21, USA).

3. RESULTS and DISCUSSION

3.1. Qualitative anatomical characteristics

The anatomical characteristics are presented in Fig. 2 A-H. The root wood showed relatively indistinct growth ring boundaries, because

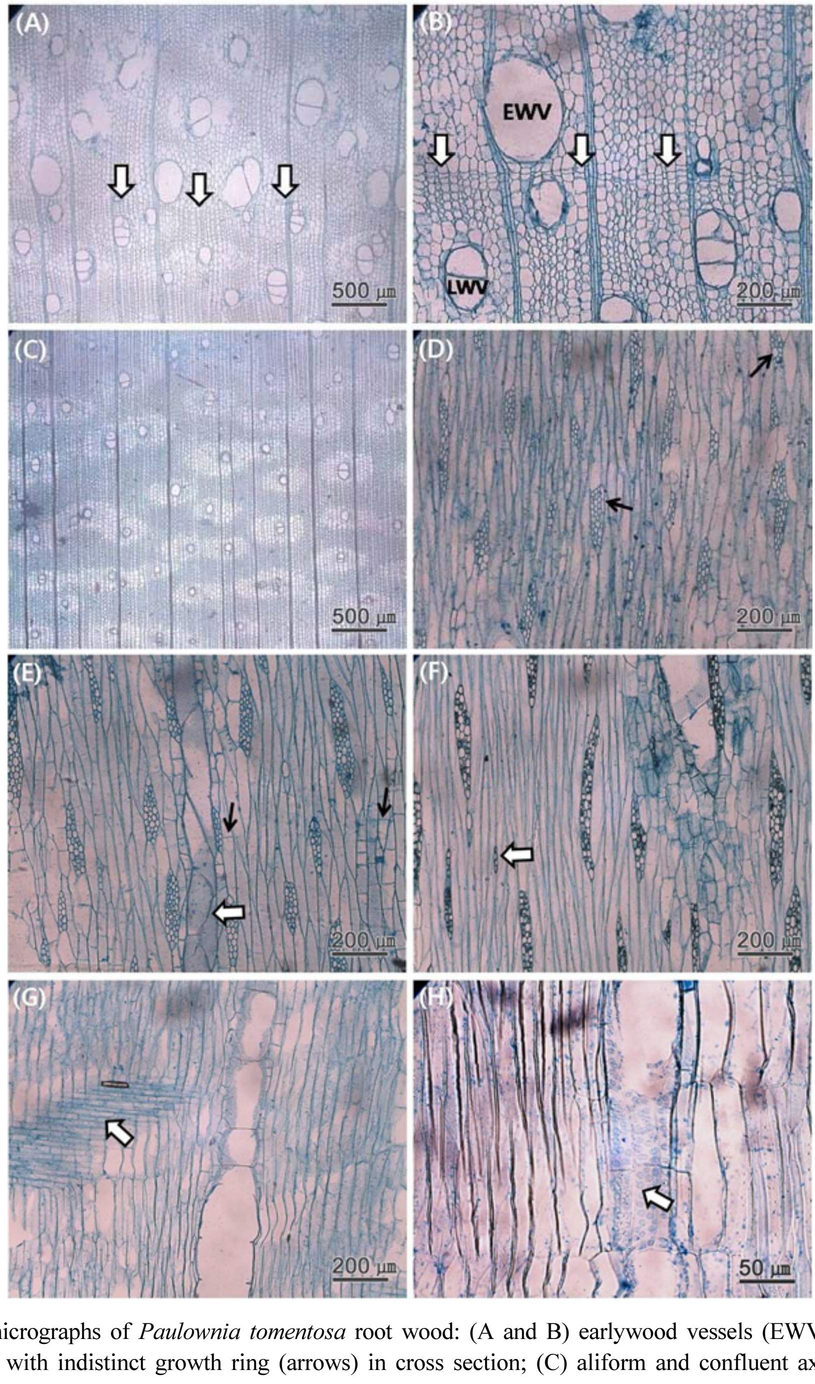

Fig. 2. Light micrographs of *Paulownia tomentosa* root wood: (A and B) earlywood vessels (EWV) and latewood vessels (LWV) with indistinct growth ring (arrows) in cross section; (C) aliform and confluent axial parenchyma in a cross section of latewood; (D) top part with sheath cells; (E) middle part with septate axial parenchyma (black arrows) and simple perforation plates (white arrow) in tangential section; (F) base part with uniseriate ray (white arrow); (G) procumbent rays in radial section; (H) alternate intervascular pits (white arrow).

of a less narrow zone of flattened axial parenchyma cells between the earlywood and latewood (Fig. 2 A and B). The root wood vessels were solitary, occurred in radial multiples of 2 to 3, and were occationally clustered (Fig. 2 A and B). Axial parenchyma was aliform and confluent (Fig. 2 C). The wood rays consisted mostly of 2 to 4-seriate cells, along with occasional uniseriate, and were surrounded by septate and nonseptate axial parenchyma (Fig. 2 D - F). Sheath cells were present, but only rarely (Fig. 2 D). Ray cells displayed procumbent forms (Fig. 2 G and H). Furthermore, vessel perforation plates were simple, and the intervascular pits alternated (Fig. 2 E and H). As a result, the growth rings were indistinct in the root wood, whereas they were distinct in stem and branch wood (Jeong *et al*., 2008; Lee, 1994; Park *et al*., 1981; Qi *et al*., 2014). These results also agreed with Fayle (1968b), Patel (1971), Stokke and Manwiller (1994), and Lee and Eom (2011).

3.2. Quantitative anatomical characteristics

Anatomical characteristics of *Paulownia tomentosa* root wood are summarized in Table 2. The vessel numbers were 5.8, 5.0, and 4.5 per mm^2 in top, middle, and base parts of root wood, respectively. These differences were significant with the top part showing the highest value among them. The vessel numbers in NP and NB wood were similar, with no significant difference between them. The average vessel number in root wood was less than compared with that in branch wood, which was approximately 10 per mm^2 (Qi *et al*., 2014).

The tangential diameters of vessels in root wood were 186.0, 182.2, and 182.5 μm, whereas the radial diameters were 249.6, 238.5, and 246.5 μm in top, middle, and base parts, respectively. The vessel diameters did not distinctly differ among the root parts, and no significant difference were identified between NP and NB wood. The average tangential vessel diameter in branch wood was 180.0 μm and the radial dimeter 210.2 μm (Qi *et al*., 2014). Overall, there were no distinct differences in vessel diameter between root wood and branch wood.

The cell wall thickness of wood fibers in root wood was 3.4, 3.4, and 3.6 μm in tangential direction, and 3.2, 4.2, and 4.0 μm in the radial direction of top, middle, and base parts, respectively. No significant statistical differences were noted in cell wall thickness among the different root parts. Furthermore, there was no difference in the cell wall thickness between NP and NB. The cell wall thickness was thicker in branch wood than in root wood, because of the gelatinous layer existing in cell walls of the branch wood (Qi *et al*., 2014).

The width of wood fiber was 29.0, 28.8, and 28.3 μm, and the length of wood fibers was 725.2, 746.0, and 772.5 μm in top, middle and base parts, respectively. The fiber width and length were not different among the root parts. No significant differences were displayed in fiber width and length between NP and NB. The fiber width in root wood was similar to that in

Table 2. Anatomical characteristics of the different *Paulownia tomentosa* root wood, separated by root parts and their near pith (NP*) and near bark (NB*) areas

Characteristics	Top			Root			Base			P-value
	NP*	NB*	Mean	NP*	NB*	Mean	NP*	NB*	Mean	
Vessel number/mm^2	6.0 ± 0.7	5.6 ± 0.8	5.8 A ± 0.1	5.2 ± 0.8	4.8 ± 1.1	5.0B ± 0.1	4.7 ± 0.7	4.2 ± 1.1	4.5C ± 0.2	0.001
Diameter (μm) Tangential	201.7 ± 12.1	170.3 ± 12.5	186.0A ± 11.1	183.4 ± 2.3	181.0 ± 8.3	182.2A ± 0.8	174.5 ± 23.8	190.5 ± 4.4	182.5A ± 5.7	0.30
Diameter (μm) Radial	263.7 ± 21.4	235.4 ± 21.8	249.6A ± 10.0	231.8 ± 19.4	245.2 ± 19.7	238.5A ± 4.7	219.0 ± 24.5	273.9 ± 14.6	246.5A ± 19.4	0.25
Wall thickness (μm) Tangential	3.2 ± 0.2	3.5 ± 0.2	3.4A ± 0.2	3.3 ± 0.1	3.5 ± 0.3	3.4A ± 0.1	3.3 ± 0.6	3.8 ± 0.1	3.6A ± 0.4	0.19
Wall thickness (μm) Radial	3.2 ± 0.5	3.2 ± 0.1	3.2A ± 0.1	3.7 ± 0.4	4.6 ± 0.1	4.2B ± 0.60	3.8 ± 0.1	4.2 ± 0.6	4.0B ± 0.3	0.13
Fiber length (μm)	709.0 ± 5.8	741.3 ± 10.5	725.2A ± 22.8	715.3 ± 10.7	776.7 ± 18.5	746.0B ± 43.4	751.1 ± 36.6	793.9 ± 22.6	772.5B ± 30.3	0.122
Fiber width (μm)	28.8 ± 7.9	29.3 ± 6.4	29.0A 0.4	28.6 ± 7.5	29.1 ± 8.7	28.8B ± 0.4	28.4 ± 5.7	28.2 ± 6.2	28.3B ± 0.1	0.100
Ray Number/mm^2	15.4 ± 0.6	13.0 ± 0.1	14.2A ± 1.7	12.4 ± 3.3	11.7 ± 1.1	12.1B ± 0.5	11.7 ± 3.2	10.1 ± 2.1	10.9B ± 1.1	0.009
Width (μm)	38.3 ± 4.3	37.3 ± 3.2	38.0A ± 0.4	50.7 ± 1.6	42.9 ± 0.4	46.8 B ± 5.5	58.1 ± 1.3	46.5 ± 4.3	52.3 B ± 4.2	0.003
Height (μm)	286.1 ± 21.4	280.3 ± 26.1	283.2A ± 4.1	318.8 ± 5.4	303.6 ± 17.3	311.2B ± 10.8	339.9 ± 23.5	310.2 ± 38.7	325.1B ± 21.0	0.005

Notes: means within a row followed by the same capital letter are not significantly different at 5% significance level using Duncan's test.

stem wood, whereas the root wood fiber length was shorter than in stem wood (Jeong *et al*., 2008; Lee, 1994). Furthermore, fiber length in root wood was slightly shorter than in branch wood,which had an average value of 800 μm (Qi *et al*., 2014).

The average ray numbers of root wood were 14.2, 12.1, and 10.9 in the top, middle and base parts, respectively. Statistical analysis showed that the ray numbers were significantly different among the root parts (Table 2), and the ray numbers decreased from the top of the root wood to the base. There were no differences in ray numbers between NP and NB. Furthermore, in our previous study, branch wood ray numbers were ca. 18 per mm^2 (Qi *et al*., 2014), which makes the ray numbers of root wood lower than those of branch wood.

Wood ray width was 38.0, 46.8, and 52.3 μm, and ray height was 283.2, 311.2, and 325.1 μm in the top, middle, and base parts of root wood, respectively. The ray width and height were significantly different among the root parts, and increased from the top to the base part. The ray width and height in NP were a little higher than those in NB. Interestingly, the ray width and height in the root wood were higher than in the branch wood, which had a

Table 3. Crystalline characteristics in *Paulownia tomentosa* root wood, separated by root parts and their near pith (NP*) and near bark (NB*) areas

Experimental parts.		Crystallinity (%)	Crystallite width (nm)
Top	NP*	45.3	2.78
	NB*	49.2	2.78
Middle	NP*	42.3	2.70
	NB*	46.9	2.68
Base	NP*	42.2	2.58
	NB*	44.8	2.87

ray width of 34.5 μm, and a ray height of 227.7 μm (Qi *et al*., 2014).

3.3. Crystalline characteristics

The crystalline characteristics of *Paulownia tomentosa* root wood are shown in Table 3. The relative crystallinity of root wood was slightly different in the top, middle, and base parts (Table 3). Furthermore, the relative crystallinity in NB was a somewhat higher than that in NP. The crystallinity in NB varied from 49.2% (top) to 44.8% (base), whereas the crystallinity in NP was 45.3% (top), 42.3% (middle) and 42.2% (base), respectively. However, there was no obvious trend for crystallite width differences among the different root parts. The crystallinity of branch wood, which was 61.9%, showed higher value than that of root wood (Qi *et al*., 2014). This difference in relative crystallinity, like the cell wall thickness difference, can be explained by the presence of the gelatinous layer in the branch wood cell walls (Goto *et al*., 1978; Harada and Goto, 1982; Lee *et al*., 1997; Lee and Kim, 1993).

4. CONCLUSION

Anatomical characteristics of root wood from *Paulownia tomentosa* were investigated. Overall, the root wood growth rings were indistinct in root parts. Furthermore, the vessels in the root wood appeared solitary, with radial multiples of 2 to 3, and were occasionally clustered. Some sheath cells and septate axial parenchyma were additionally observed in the wood samples.

The vessel and ray numbers, as well as the ray width and height were significantly different among the root wood top, middle and base parts. The ray numbers decreased from the top to base parts, while the ray width and height increased. In contrast, there were no significant differences in vessel diameters, cell wall thickness, and wood fiber width and length among the different root parts. Furthermore, the top part crystallinity was slightly higher than in the middle and base parts of root wood. There were no big differences between the anatomical characteristics of the NB and NP. Overall, the top, middle, and base parts of root wood differed in some of their anatomical characteristics.

ACKNOWLEDGEMENT

This study is supported by 2015 Research Grant from Kangwon National University (No. 520150258). Yue Qi also sincerely thanks the ACES-KNU scholarship of Kangwon National University for financial support from 2012.

REFERENCES

Alexander, L.E. 1969. X-ray diffraction in polymer science. Wiley-Interscience, Amsterdam pp: 423～424.

Fortunel, C., Ruelle, R., Beauchene, J., Fine, P.V.A., Baraloto, C. 2014. Wood specific gravity and anatomy of branches and roots in 113 Amazonian rainforest tree species across environmental gradients. New Phytologist 202: 79～94.

Goto, T., Harada, H., Saiki, H. 1978. Fine structure of cellulose microfibrils in poplar gelatinous layer and valonia. Wood Science and Technology 12: 223～231.

Harada, H., Goto, T. 1982. The structure of cellulose microfibrils in Volonia. "cellulose of other natural polymer systems". Malcolm Brown, Jr., Eds., Plenum press: 383～401.

IAWA Committee. 1989. IAWA List of microscopic features for hardwood identification. IAWA Bulletin n.s. 10(3): 219～332.

Jacobsen, A.L, Agenbag, L., Esler, K.J., Pratt, R.B., Ewers, F.W., Davis, S.D. 2007a. Xylem density, biomechanics and anatomical traits correlate with water stress in 17 evergreen shrub species of the Mediterranean-type climate region of South Africa. Journal of Ecology 95: 171～183.

Jeong, S.H., Park, B.S. 2008. Wood properties of the useful tree species grown in Korea. Korea Forest Research Institute 29: 348～368.

Jourez, B., Riboux, A., Leclercq, A. 2001. Anatomical characteristics of tension and opposite wood in young inclined stem of Poplar (Populus euramericana cv 'Ghjoy'). IAWA Journal 22: 133～157.

Kim, J.H., Jang, J.H., Ryu, J.Y., Hwang, W.H., Febraianto, F., Kim, N.H. 2013. Comparison of anatomical characteristics of White Jabon and Red Jabon grown in Indonesia. Journal of Korean Wood science and technology 41(4): 327～336.

Kim, J.H., Jang, J.H., Kwon, S.M., Febraianto, F., Kim, N.H. 2012. Anatomical properties of major planted and promising species growing in Indonesia. Journal of Korean Wood science and technology 40(4): 244～256.

Korean standards association. 2004. KS F 2198.

Lee, M.R., Eom, Y.G. 2011. Comparative wood anatomy of stem and root in Korean-grown Yellow-poplar (*Liriodendron tulipipfera L.*). Journal of Korean Wood science and technology 39(5): 406～419.

Lee, S.H., Hwang, W.J., Kim, N.H. 1997. Some anatomical characteristics in tension and opposite wood of *Quercus mongolica* Fisher. Journal of Korean Wood science and technology 25(3): 43～49.

Lee, W.Y., Kim, N.H. 1993. Crystal structure of tension wood by x-ray diffraction method. Journal of Korean Wood Sciencen and Technology 21 (4): 65～73.

Lee, P.W. 1994. The structures of Korean domestic woods. -Microscopic anatomy- JeongMinSa, Seoul, Republic of Korea.

Lillie, R.D. 1977. Conn's biological stains. Williams and Wilkins Co., Baltimore.

Matsumura, J., Butterfield, B.G. 2001. Microfibril angles in the root wood of *Pinus radiata* and *Pinus nigra*. IAWA Journal 22: 57～62.

Palhares, D., de Paula, J.E., Rodringues Pereira, L.A., dos Santos Silveira, C.E. 2007. Comparative wood anatomy of stem, root and xylopodium of *Brosimum gaudichaudii* (Moraceae). IAWA Journal 28(1): 83～94.

Patel, R.N. 1971. Anatomy of stem and root wood of *Pinus radiata* D. Don. New Zealand Journal of Forest Science 11: 37～49.

Poorter, L., McDonaldM, I., Alarcon, A., Fichtler, E., Licona, J.C., PenaClaros, M., Sterck, F., Villegas, Z., Sass-Klaassen, U. 2010. The importance of wood traits and hydraulic conductance for the performance and life history strategies of 42 rainforest tree species. New Phytologist 185: 481～492.

Qi, Y., Jang, J.H., Park, S.H., Kim, N.H. 2014. Anatomical and Physical Characteristics of Korean Paulownia (*Paulownia coreana*) Branch Wood. Journal of Korean Wood science and technology 42(5): 510～515.

Rao, R.V., Sharma, B., Dayal, R. 1989. Anatomy of aerial rootwood of *Sonneratia caseolaris* (L.) Engler (*Sonneratioideae*). IAWA Bull.n.s 10(4): 374～378.

Schuldt, B., Leuschner, C., Brock, N., Horna, V. 2013. Changes in wood density, wood anatomy and hydraulic properties of the xylem along the root-to-shoot flow path in tropical.

rainforest trees. Tree Physiology 33: 161～174.

Segal, L., Creely, J.J., Martin, A.E., Conrad, C.M. 1959. An empirical method for estimating the degree of crystallinity of native cellulose using the X-ray diffractometer. Textile research Journal 29: 786～794.

Stokke, D.D., Manwiller, F.G. 1994. Pro-portions of wood elements in stem, branch, and root wood of black oak (Quercus velutina). IAWA Journal 15(3): 301～310.

Von Aufsess, B.H. 1973. Microscopic scope of lignifications by staining methods. European Journal of Wood and Wood Products 31(1): 24～33.