Enhancing the potential of African Blackwood, *Dalbergia melanoxylon*, through sustainable forest utilization: a valuable tree species in Tanzanian miombo forest

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CONTENTS

EXECUTIVE SUMMARY

African Blackwood, *Dalbergia melanoxylon*, is one of the most valuable timber species in the world. The recent status of this species, however, is threatened by both continuous overharvesting and low regeneration ability. Recent concerns about the sustainability of this species, such as the IUCN red list or CITES, has led to a rapid and strong interest in resource conservation. African Blackwood is the national tree of Tanzania, and is mainly distributed among the semi-dry woodland of sub-Saharan African countries, including Tanzania and Mozambique. It commonly occurs in deciduous woodland, coastal bushland and wooded grassland, and individuals are frequently found in "Miombo woodlands". Since the early 19th century, African Blackwood has been utilized as an irreplaceable material in the manufacture of woodwind instruments (*e.g.*, clarinet, oboe and piccolo). The purplish-black colored heartwood is valued due to the precious advantages of the material's properties, as well as its appearance. The density of heartwood is comparatively higher than that of other general hardwood species (over 1.1 g/cm^3), which tends to affect processability in sawmill factories. However, the smooth surface of processed timber enhances product quality. In addition, a comparatively lower loss factor compared to other species has contributed to the specific brilliant sound of woodwinds. Classical music players generally prefer the final products made from this timber. Finally, since this tree is the only valuable species in local community forests, its utilization can contribute to local development.

The main objective of this research was to clarify the potential for sustainable forest management in local communities based on sustainable conservation of African Blackwood. Currently, there are several issues with the resource sustainability of African Blackwood related to the efficiency of timber usage. The demand for African Blackwood depends on the musical instrument industry, and most of the harvested volume is wasted to meet the quality requirements of the production process. Only 10 % of harvested volume can generally be used in this process, and such inefficient usage promotes overharvesting. In this study, two approaches were examined to address the current issues: (1) promoting the conservation and cultivation of high-quality African Blackwood; and (2) improving usage efficiency of harvested timbers in the present commercial value chain.

In Chapter 2, "Potential for sustainable forest utilization in Tanzanian community forest: Environmental factors and wood qualities of African Blackwood", the silvicultural potential focused on the sustainable cultivation of African Blackwood was studied in a Tanzanian Miombo natural forest. The relationship between distribution and environmental factors, *i.e.*, surrounding

vegetation and soil, was examined to clarify the natural growth condition of standing African Blackwood. Multiple forest surveys were conducted in the local community forests of the southern part of Tanzania, Kilwa District, Lindi Region. In addition, the physical properties of standing trees were evaluated by measuring their stress-wave velocity in the field survey. The findings suggested that African Blackwood could survive under various environmental conditions with intensive population, whereas tree growth (growth form and appearance) was affected by the surrounding conditions, particularly the soil conditions. Furthermore, human activities such as forest fire and agriculture might influence growth form. By contrast, the stress-wave velocity of standing trees was not affected by environmental conditions. It was suggested that there was no significant effect of external factors on the real physical properties of timber materials. Timber usage generally depends on tree appearance. Forest management should focus on producing high-yield African Blackwood trees to achieve sustainable industrial use. Moreover, methods to promote the growth process are needed in natural forest.

In Chapter 3, "Improvement of current African Blackwood usage: application of wood flow forming", the application of wood flow forming technique was investigated to determine if it could be applied to utilize wasted African Blackwood timbers effectively. The study focused on the deformation characteristics of heartwood, in which extractives comprised over 15wt%. These deformation characteristics were examined *via* the free compression test. Specimens were compressed in the radial direction at 120 °C, which dramatically deformed in the tangential direction. It was suggested that such flow phenomenon depended on both the extractives and moisture. The thermal behavior of extractives was also analyzed in the dynamic mechanical analysis using a rheometer. The results indicated that the modulus of transverse elasticity was relevant to the thermal behavior of ethanol/benzene (1:2, v/v) soluble extractives. The extractives of heartwood exhibited softening in the range over 50 °C. Furthermore, such extractives existed only in the heartwood. These findings suggested the potential of flow forming to improve the current usage of wasted timbers in local sawmill factories.

In Chapter 4, "Challenges for promoting sustainable forest utilization: Biological performance of local trees", the further utilization of other local species as well as African Blackwood was studied as the complementary studies in the effort to achieve sustainable local forestry. The biological performance, *i.e.*, the durability against termite and wood decay fungi, of African Blackwood was evaluated in comparison to the heartwoods of other Tanzanian local tree species such as *Pterocarpus angolensis*, *Afzelia quanzensis* and *Millettia sthulmannii*. The heartwood of

African Blackwood was shown to have strong biological performance, whereas the sapwood was obviously less resistant to termite and fungal attacks. In addition, the heartwood of other species like those listed above, also showed a higher biological performance than that of African Blackwood. High-density species showed higher durability than low-density species, with extractives possibly contributing to their durability. The highest levels of extractives were shown to occur in the heartwood of African Blackwood: *ca.* 25 wt% of ethanol/benzene-soluble extractives, *ca.* 13 wt% of water-soluble extractives. The other high-durability species, *Afzelia quanzensis* and *Millettia sthulmannii*, were found to be composed of higher amounts of extractives than those of general hardwood species; wood chemical analysis, however, revealed differences in components. These findings suggested the further potential of local species utilization. Unused species in local forest might be utilized to meet domestic and/or global demands.

A sustainable and healthy forest should be based on sustainable utilization. A well-established timber market that continuously provides benefits to the local forest supports such utilization. Thus, forest management should focus on producing valuable timber. To achieve sustainable forest management, stakeholders must create a business model to maximize each benefit. The current market for African Blackwood in the musical instrument industry is comparatively stable and valuable; the findings obtained in this study showed, however, there is room to improve the current timber usage. High-quality African Blackwood might be provided by controlling the growth characteristics, because the physical properties were not related to the standing environment. In particular, controlled gaps in natural forest might improve growth form due to light demands. Such forest management could be achieved by effective harvesting of surrounding species. The potential of other local species revealed here should useful for further developing the timber market at a global level. In addition, the current supply chain for African Blackwood might be dramatically improved by the application of wood flow forming technique. Effective use of African Blackwood waste could contribute to creating new value for the timber in Tanzania and other origin countries, as well as improving material usage. Consequently, the obtained results can contribute to establishing the sustainable forest business model. African Blackwood is expected to become a valuable species for local communities in semi-dry areas of African countries together with the effective utilization of some other local species.

CHAPTER 1

RESEARCH BACKGROUND

1.1 African Blackwood

African Blackwood (ABW) (Fig. 1.1), *Dalbergia melanoxylon*, locally known as Mpingo in Swahili, is now widely distributed through sub-Saharan African countries such as Tanzania, Mozambique, Kenya, Ethiopia, Nigeria and even Senegal. Currently, harvestable-sized trees (over 24-cm diameter at breast height (DBH) regulated in Tanzania) are observed intensively in the coastal areas of East African countries such as Tanzania and Mozambique. ABW commonly occurs in deciduous woodland, coastal bushland and wooded grassland, and individuals are frequently found in miombo woodland, which is a semi-deciduous formation with a tree layer characterized by an abundance of three genera: *Brachystegia*, *Julbernardia* and *Isoberlinia* (Campbell 1996; White 1983) (Fig. 1.2). The miombo woodland covers approximately 10 % of the African continent (White 1983). It is estimated to contain over 300 tree species which are commonly dominated by Fabaceae trees. The woodland also supports the livelihood of 100 million people who rely on products from this distinct and unique biome (Campbell *et al.* 2007).

ABW trees naturally grow in clusters, and their population density has been estimated as 9–90 trees/ha (Gregory *et al.* 1999; Opulukwa *et al.* 2002; Mariki and Wills 2014). In Tanzania, ABW is frequently observed in the southern part of the Kilwa District, Lindi Region. Lindi Region is the fourth largest in Tanzania, with a land area of ca. 6.7 million ha. About 50 % of the land is covered by forest (Miya *et al.* 2012) (Fig. 1.3). Mean annual rainfall is 750–1500 mm/year (Fig. 1.3), and the forest area is composed of miombo woodland in conjunction with the coastal forest. The Kilwa District is located in the northern part of the Lindi Region, and has a larger forest coverage rate than other areas in Tanzania: 70 % of the land is covered by forest. The District has some cash crop cultivations such as sesame and cashew that contribute to local livelihoods (Miya *et al.* 2012; JICA and Yamaha 2019).

Fig. 1.1 An African Blackwood tree (Nanjirinji-A village, Kilwa District, Lindi Region, Tanzania).

Fig. 1.2 A representative photo of Tanzanian miombo forest (Nanjirinji A village, Kilwa District, Lindi Region, Tanzania).

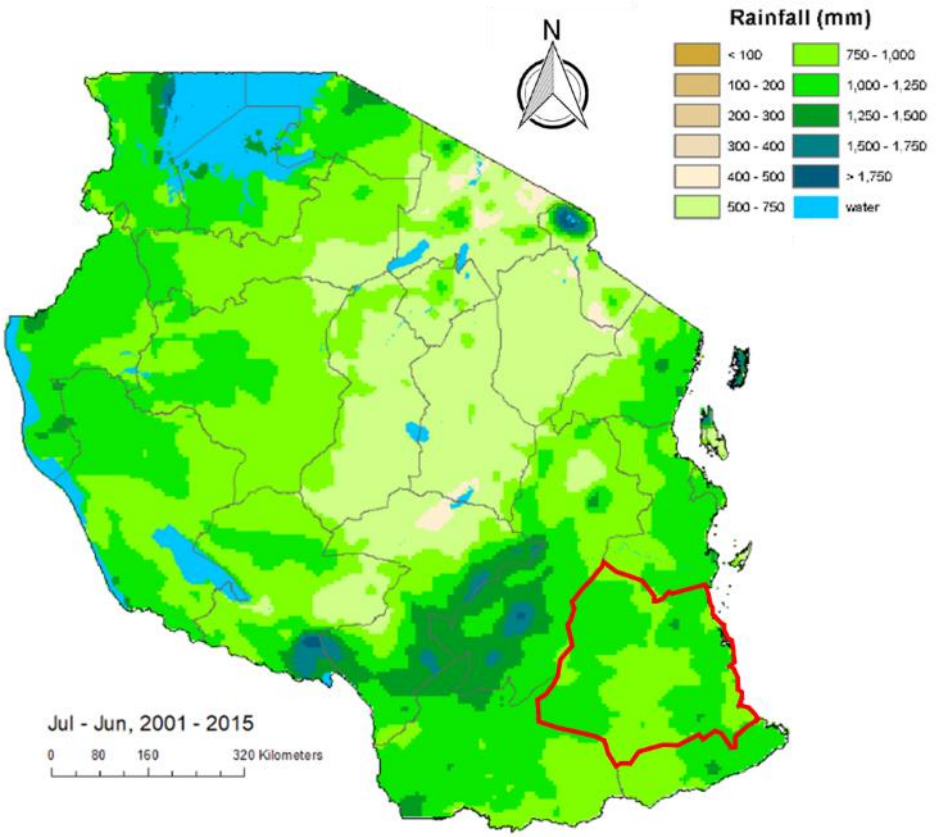


Fig. 1.3 Location of Lindi Region in Tanzania (outlined in red line) on map of average annual precipitation of each region (adapted from the database of USGS/USAID, 2018. https://earlywarning.usgs.gov/fews/product/286).

1.2 History of African Blackwood utilization

ABW is Tanzania's national tree and has historically been an important species in local areas (Bryce 1967; Mbuya *et al.* 1994; Ball 2004; Cunningham 2016). The timber has been locally used for traditional carvings (Cunnigham 2016) and charcoals (Miya *et al.* 2012). The heartwood (Fig. 1.4, 1.5), which is called grenadilla in musical instrument industry, is especially considered an irreplaceable material for woodwind instruments, such as clarinets, oboes, piccolos and bagpipes, due to its specific characteristics. It is normally purplish-black in color (Fig. 1.5), and extremely heavy, with 1.1–1.3 g/cm^3 of air-dried density (Malimbwi and Luoga 2000; Sproßmann *et al.* 2017). Meanwhile the damping coefficient (tanδ) in vibration properties is lower than other general hardwood species (Brémaud *et al.* 2012). Such characteristics contributed to a brilliant sound suitable for orchestra music, and most woodwinds today are made from ABW. In the musical instrument industry, other *Dalbergia* species have been also utilized as materials. *Dalbergia retusa*,

which is called as cocobolo, native to Latin America, has been partly used for clarinets, while *Dalbergia latifolia*, which is indigenous to South and Southeast Asia, is mainly used for the fingerboard, backboard, sideboard and other small parts of guitars. *Dalbergia stevensonii*, another Latin-American species known as Honduras rosewood, is used for the marimba. In addition, *Dalbergia nigra*, called as Jacaranda or Brazilian rosewood and native to Brazil, has long been used for musical instruments (Praciak *et al.* 2013). However, overexploitation of *D. nigra* over the centuries led to fears of its extinction (Praciak *et al.* 2013), and it was banned from international trade in Appendix I of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) in 1992. The industrial usefulness of *Dalbergia* species has been regarded not only for local timber use but also as the tone wood parts of instruments worldwide.

Fig. 1.4 A cross-section of ABW log largely consisting of heartwood.

Fig. 1.5 Processed ABW timbers at a local sawmill.

Since the early 19th century, ABW timber has been traded to European countries for woodwind products (Cunningham *et al.* 2015). The industrial production of woodwind instruments first occurred during the Industrial Revolution (Cunningham 2016). The clarinet was developed around the 1740s in Nuremberg, Germany (Cunningham 2016). European woodwinds were initially made from European boxwood (*Buxus sempervirens*), which was one of the heaviest timbers available in Europe. Although its slow growth and small stem were not user-friendly, its density was useful for woodwinds (ABCP website). However, the modern standard clarinet is made from ABW as previously noted, probably due to its dimensional stability and specific black color. Dimensional stability is especially important for woodwinds, which tend to be affected by changes in humidity due to blowing performance, as well as the outside environment. The musician's breath always creates a dramatic difference in humidity inside and outside the instrument's cylindrical body. Such differences sometimes cause cracks, which seriously affect pitch. When trade routes from tropical countries were established during the colonial period, several tropical timbers including ABW were brought to European countries (ABCP website). In the 19th Century, ABW became one of the substitutions for woodwind materials.

1.3 Inefficient resource usage due to limited demand

The demand for ABW generally depends only on the musical instrument industry. As a result, the material utilization is liable to be inefficient compared to that of normal timber.

ABW normally takes 70–100 years from seed germination to harvestable trees, and a tree's characteristics seriously affect timber processing. General tree characteristics have been reported as follows: average height, 5–7 m; multi-stemmed with a bole circumference normally < 120 cm; and irregularly shaped crown (Sacánde *et al.* 2007; Lovett 1987). The average DBH is less than 38 cm, and trees have pale gray to grayish-brown bark, that is papery, fairly smooth, and flaking in long narrow strips (Bryce 1967). Small trees can cause serious problems in the operation of sawmills due to lateral twists, deep fluting and knots including cracks (Lovett 1987). Such defects may affect the general performance of musical instruments. For example, the internal surface condition of the wood can impact acoustic attenuation in the cylindrical resonators of woodwind instruments (Boutin *et al.* 2017).

As a result, sawmills can generate only a small amount of the necessary quality timber, with an actual timber yield of 9 % (Gregory *et al.* 1999). This value is equal to around 5 % of the harvested volume in standing tree, which is extremely lower timber yield compared to general hardwood processing. Finally, due to the cylindrical shape and typical production yield, only around 20 % of the volume of shipped material remains in the final product (JICA and Yamaha 2019) (Fig. 1.6). Such inefficient utilization has made ABW one of the most highly priced timbers in the world, with a market rate of US$14,000–20,000 per m^3 (Cunningham *et al.* 2015; Jenkins *et al.* 2002). Additionally, intensive harvesting due to such utilization has threatened the species' sustainability (Jenkins *et al.* 2002; Hamisy and Hantula 2002). In fact, ABW has been designated as "near threatened" on the IUCN (International Union for Conservation of Nature) red list since 1998 (WCMC 1998), and international trade of all existing *Dalbergia* species including ABW has been restricted worldwide in Appendix II of the CITES since 2017 (UNEP-WCMC 2017). Exploitation for industrial use has been threatened as in the case of *D. nigra* noted previously.

Fig. 1.6 Schematic diagram explaining general ABW utilization from Tanzania to the final production company (JICA and Yamaha 2019).

1.4 Forest conservation in Southern Tanzania

ABW is an economically important tree in many African woodlands, supporting local communities. Hence, the sustainable conservation of ABW resources is vitally important in terms of local development, as well as for the musical instrument industry. In Tanzania, the Mpingo Conservation & Development Initiative (MCDI), a local non-government organization (NGO), is currently working for sustainable forest conservation based on a Forest Stewardship Council (FSC)-certified forest in the Kilwa District. The MCDI focuses on a participatory forest management (PFM) system, which acts as a basic legal facilitator for reducing emissions from deforestation and forest degradation plus the sustainable management of forests, and the conservation and enhancement of forest carbon stocks (REDD+). It gives local communities control and ownership of their forest resources, including timber, through demarcated village land forest reserves (VLFRs), which would otherwise be controlled by the government (URT 2007; Khatun *et al.* 2017).

In the PFM promoted by the MCDI, the profit generated through the timber harvesting leads directly to the public income of the village. Moreover, a part of that income is invested in forest management activities such as forest patrol, boundary establishment and fire management (JICA and Yamaha 2019). ABW has become one of the most important species for income generation in

local communities. Nanjirinji village in the Kilwa District, for example, has continuously earned revenues by timber harvesting activities (Table 1.1).

Table 1.1 Annual revenues earned from timber harvesting activities in Nanjirinji Village, Kilwa District (JICA and Yamaha, 2019).

VILLAGE NAME	FINANCIAL YEAR	REVENUE EARNED (TZS)	REVENUE EARNED (USD)	VOLUME HARVESTED (M^3)
Nanjirinji A (Mbumbila A)	2016/2017	318,744,806	138,585	1,336.18
Nanjirinji A (Mbumbila B)		11,635,480	5,059	34
Nanjirinji B		18,606,756	8,090	73.4
Nanjirinji A (Mbumbila A)	2017/2018	37,469,051	16,291	142.6
Nanjirinji A (Mbumbila B)		76,353,800	33,197	283.01
Nanjirinji B		5,830,000	2,535	20

1 USD = 2,300 TZS

1.5 Silvicultural practice

Planting is an effective way of sustaining and promoting regeneration of ABW resources in natural forest. ABW planting has not yet been shown to be economically viable, given the long rotation period of 70–100 years to reach harvestable size. Therefore, planting practices have not yet been examined scientifically. However, growth of planted or natural trees was observed in annual increments of 0.3–1 m in height and 1–2 cm in diameter for the initial 5 years (Praciak *et al.* 2013). In the northern part of Tanzania, Moshi Rural District, Kilimanjaro Region, experimental planting has been conducted by a local NGO, the African Blackwood Conservation Project (ABCP). The DBH of planted trees in an experimental site was observed to increase 2–3 cm per year in the preliminary survey conducted in 2015.

According to the experimental trials, seedlings could be transplanted to the forest in 1-year cycles. They were transplanted to tubes or pods 4-5 weeks after germination, and planted after 6–7 months (Praciak *et al.* 2013; JICA and Yamaha 2019). The initial spacing of 2 m × 2 m resulted in well-controlled branching with periodical thinning (Praciak *et al.* 2013; JICA and Yamaha 2019). Stem form was also improved by raising trees under medium shade provided by fast-growing

softwood trees (Nshubemuki 1993). Planted trees were likely to grow up faster than natural trees with high quality controlled by silvicultural practices.

Planting activities including seedling production could potentially function to improve the local incentive for forestry activities in addition to sustaining tree resources. JICA and Yamaha (2019) conducted a pilot study of ABW planting in a village of the Kilwa District (Nanjirinji A Village and Nanjirinji B Village), in cooperation with the MCDI. This was the first case of community-based ABW planting focused on the industrial use of planted seedlings (Nakai 2018; JICA and Yamaha 2019). Nanjirinji Village is in the southern part of the Kilwa District, and manages over 60,000 ha of community forest. It has the largest harvested volume of ABW logs in the MCDI's areas. In the project, VNRC (Village National Resource Committee) members have transplanted 2000-3000 seedlings per year. These members were selected to conduct forest management. The seedlings cultivated in the nursery site (Fig. 1.7) were transplanted by enrichment planting. In all, a total of *ca.* 5000 seedlings were planted to the 2.5 ha designated area in the 2 years after 2017 (JICA and Yamaha 2019). JICA and Yamaha (2019) reported that the VNRC members have been operating seedling production according to a schedule (Fig. 1.8). The pilot activities could provide local benefits such as job-creation.

Fig. 1.7 Seedlings cultivated in the nursery site. Left: matured seedlings, Right: transplanting seedlings after 2-4 weeks from the seedbed to polyethylene tubes.

Fig. 1.8 Example nursery management schedule. “Ratiba ya umwagiliaji wa kijaru cha kuzarisha miche ya Mpingo” in Swahili means “Schedule table for irrigation cultivating ABW seedling”.

1.6 Further timber utilization to promote local forestry

Further utilization of other local species is needed to promote sustainable forest management. The local forest where ABW is frequently distributed has other Fabaceae species, including lesser-known timber species. Important species in the local forest, including *Afzelia quanzensis*, *Pterocarpus angolensis*, and *Millettia sthulmannii*, have frequently been traded internationally. Over 90 % of that, however, was as uncertified timber (Cunnigham 2016).

Afzelia quanzensis trees occur in a range of habitats in East Africa, from the coastal and dune forests of the Mozambique coastalplain through to miombo woodlands (Cunnigham 2016). This species, locally called Mkongo in Swahili, and its timber has been widely used for furniture, exteriors, house construction, etc., in Tanzania. *Pterocarpus angolensis* is widespread throughout deciduous broadleaf savannas and miombo woodlands in Eastern and Southern Africa (Cunnigham 2016). The stem is normally straight and the diameter is generally larger than that of ABW, with logs that are comparatively easier to process. It has been also utilized for furniture and house construction. *Millettia sthulmannii* is another Fabaceae species, and its hard, dark-colored

heartwood has the potential for use in guitar fingerboards. This species is called Mpangapanga in Swahili, and is locally known as a useful timber.

These species are often observed with ABW trees in miombo woodlands, but their use has been limited compared to the industrial utilization of ABW. Sustainable timber utilization could create local benefit through domestic and/or international timber trade. It could contribute to improving local livelihoods, and promoting forest management by investing the profit generated in timber sales. MCDI has already been promoting such utilization in cooperation with private companies, and is implementing the conservation of these species in addition to ABW (MCDI 2018).

1.7 Main research objective

The main goal of this research is to achieve a sustainable forest based on the effective utilization of valuable ABW timbers, which can support the development of local society as well as the businesses in developed countries. To achieve this objective, the local forest must naturally produce the high-quality timber for musical instruments due to the present limited demand. This research suggests that fundamental approaches are needed to address the current problems: (1) promoting the conservation and cultivation of high-quality ABW tree (as described in Chapter 2 and Chapter 4); (2) improving usage efficiency of harvested timbers in the present commercial value chain (as described in Chapter 3 and Chapter 4).

As described in Chapter 2, the silvicultural potential of ABW tree in natural forest should be assessed for future development of high-quality ABW tree cultivation. The surrounding environment, *e.g.*, climate factors, soil type and surrounding vegetation, potentially influence tree growth (Julin *et al.* 1993; Koch *et al.* 2004), their effects on ABW growth have been previously studied in some locations (Munishi *et al.* 2007; Munishi *et al.* 2011; Banda *et al.* 2006; Mariki and Wills 2014). Although the relationship between environmental conditions and wood quality has not yet been clarified, it can contribute to finding the possibility of sustainable forest conservation, *e.g.*, growth control, tree planting, propagation.

The additional use of wasted ABW could potentially contribute to local development as described in Chapter 3. The efficient material use can maximize timber value, and curb the decline of available resources. In Tanzania, wasted ABW is frequently used as an energy resource, *e.g.*, as charcoal and fuelwood, at an extremely lower price than that of the timber (Miya *et al.* 2012). Since

ABW has specified physical characteristics that are suitable for woodwind instruments, the additional use is suggested to maximize the present wood value.

A wood's resistance to biological attacks is a key to developing timber utilization, especially in tropical species (as in Chapter 4). The biological performance (*i.e.*, durability against both termite and fungal attacks) is generally related to extractives concentrated during the heartwood formation, as well as to wood density. The heartwood contains sufficient extractives to impact insect and decay resistance (Grace 2003), and tropical woods typically have high extractive contents. Furthermore, high-density woods have slower decay rates than low-density woods (Chambers *et al.* 2000; Chave *et al.* 2009). However, there is little information about the biological performance of ABW and other coexisting species in local forests. Species with high biological performance are potentially useful for developing further timber utilization, which brings extra benefit to local forestry.

The results obtained from this research contribute to providing useful information for achieving the sustainable utilization of ABW. Although ABW has been used globally as timber material, there are many problems with sustaining this resource. To achieve sustainable forest, resource utilization should become profitable for local business. The silvicultural strategy and sustainable forestry should be established according to the results of this research. They could then be expected to contribute to our global societies.

1.8 References

- ABCP (2019) Woodwind Instruments. https://www.blackwoodconservation.org/woodwind-instruments/ Accessed 13 June 2020.

- Banda T, Schwartz MW, Caro T (2006) Woody vegetation structure and composition along a protection gradient in a miombo ecosystem of western Tanzania. *Forest Ecology and Management* 230(1-3): 179-185.

- Brémaud I, El Kaïm Y, Guibal D, Minato K, Thibaut B, Gril J (2012) Characterisation and categorisation of the diversity in viscoelastic vibrational properties between 98 wood types. *Annals of Forest Science* 69(3): 373-386. DOI:10.1007/s13595-011-0166-z

- Boutin H, Le Conte S, Vaiedelich S, Fabre B, Le Carrou JL (2017) Acoustic dissipation in wooden pipes of different species used in wind instrument making: an experimental study. *The Journal of Acoustic Society of America* 141(4): 2840-2848. doi:10.1121/1.4981119

- Bryce JM (1967) The commercial Timbers of Tanzania. Forest Division, Ministry of Agriculture & Co-operatives, Moshi, Tanzania

- Campbell B, Frost P, Byron N (1996) Miombo woodlands and their use: overview and key issues. In: Campbell B (ed) The Miombo in Transition: woodlands and welfare in Africa, Center for International Forestry Research (CIFOR), Bogor, pp 1-10.

- Campbell BM, Angelsen A, Cunningham A, Katerere Y, Sitoe A, Wunder S (2007) Miombo woodlands: Opportunities and barriers to sustainable forest management. Harare. Centre for International Forestry Research (CIFOR), Bogor, Indonesia.

- Chambers JQ, Higuchi N, Schimel JP, Ferreira LV, Melack JM (2000) Decomposition and carbon cycling of dead trees in tropical forests of the central Amazon. *Oecologia* 122(3), 380-388. DOI: 10.1007/s004420050044

- Chave J, Coomes D, Jansen S, Lewis SL, Swenson NG, Zanne AE (2009) Towards a worldwide wood economics spectrum. Ecology Letters 12: 351-366. DOI: 10.111/j.1461-0248.2009.01285.x

- Cunningham AB, Manalil S, Flower K (2015) More than a music tree: 4400 years of *Dalbergia melanoxylon* trade in Africa. *South African Journal of Botany* 98: 167

- Cunningham AB (2016) Trade study of selected east African timber production species, in: *Proceedings of the Convention on International Trade in Endangered Species of Wild Fauna and Flora Seventeenth Meeting of the Conference of the Parties*, Johannesburg, South Africa. pp. 27-66.

- Grace JK (2003) Termite resistant wood products. Sociobiology 41(1): 123-129.

- Gregory A, Ball SMJ, Eziefula UE (1999) Tanzanian Mpingo 98 Full Report. Mpingo Conservation Project, Tanzania

- Hamisy WC, Hantula J (2002) Characterization of genetic variation in African Blackwood, *Dalbergia melanoxylon* using random amplified microsatellite (RAMS) method. Plant genetic resources and biotechnology in Tanzania, Part 1: 108-117

- Jenkins M, Oldfield S, Aylett T (2002) *International trade in African blackwood*. Fauna & Flora International, Cambridge, UK.

- JICA, Yamaha Corporation (2019) The United Republic of Tanzania, Preparatory survey on BOP Business for sustainable procurement of FSC certificated wood: Final report. Japan International Cooperation Agency, Tokyo, Japan.

- Julin K, Farr WA (1989) Stem fluting of Western Hemlock in Southeast Alaska. *U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station*, Portland, Oregon, US.

- Khatun K, Corbera E, Ball S (2017) Fire is REDD+: offsetting carbon through early burning activities in south-eastern Tanzania. *Oryx* 51(1): 43-52. DOI:10.1017/S0030605316000090

- Koch GW, Sillett SC, Jennings GM, Davis SD (2004) The limits to tree height. *Nature* 428(6985): 851.

- Lovett J (1987) Mpingo – the African blackwood. *Swara* 10: 27-28.

- Mariki AS, Wills AR (2014) Environmental Factors Affecting Timber Quality of African Blackwood (*Dalbergia melanoxylon*). Mpingo Conservation & Development Initiative, Tanzania.

- Malimbwi RE, Luoga EJ (2000) Prevalence and standing volume of *Dalbergia melanoxylon* in coastal and inland sites of southern Tanzania. *Journal of Tropical Forest Science* 12(2): 336-347.

- Miya M, Ball SMJ, Nelson FD (2012) Drivers of Deforestation and Forest Degradation in Kilwa District. Mpingo Conservation & Development Initiative, Tanzania: 1-34

- MCDI (2019) Annual Report 2017-2018. https://jwoodscience.springeropen.com/submission-guidelines/preparing-your-manuscript/original-article Accessed 21 October 2019.

- Munishi PKT, Temu RAPC, Soka G (2011) Plant communities and tree species associations in a Miombo ecosystem in the Lake Rukwa basin, Southern Tanzania: Implications for conservation. *Journal of Ecology and the Natural Environment* 3(2): 63-71.

- Nakai K (2018) Creating sustainable forests harmonized with a business for musical instruments: African Blackwood in Tanzania **(in Japanese)**. Japanese Journal of International Forest and Forestry 101: 9-13. DOI: 10.32205/jjjiff.101.0_9

- Nshubemuki L (1993) *Dalbergia melanoxylon*: Valuable Wood from a Neglected Tree. NFT Highlights 1993-1995. *Nitrogen Fixing Tree Association*, Hawaii, US.

- Opulukwa MJ, Hamza KFS, Malende YHMB (2002) Inventory of *Dalbegia melanoxylon* (Mpingo) in the southern part of Tanzania: The case of Nachingwea. *African Study Monographs* 23(1): 1-10.

- Praciak A, Pasiecznik N, Sheil D, van Heist M, Sassen M, Correia CS, Dixon C, Fyson GE, Rushforth K, Teeling C (2013) *The CABI Encyclopedia of forest trees.* CAB International, Oxfordshire, UK.

- Sacandé M, Vautier H, Sanon M, Schmit L (2007) *Dalbergia Melanoxylon* Guill. & Perr (Seed Leaflet Report No. 135), University of Copenhagen, Copenhagen, Denmark.

- Sproßmann R, Zauer M, Wagenführ A (2017) Characterization of acoustic and mechanical properties of common tropical woods used in classical guitars. *Results in Physics* 7: 1737-1742. DOI: 10.1016/j.rinp.2017.05.006

- UNEP-WCMC (2017) Review of selected *Dalbergia* species and *Guibourtia demeusei*. UNEP-WCMC, Cambridge, UK.

- URT (United Republic of Tanzania) (2007) Prime Minister's Office, Information about Lindi region, Kilwa District. http://lindi.go.tz/limdi/limdi-rural/. Accessed 1 May 2018.

- WCMC (1998) *Dalbergia melanoxylon*. The IUCN Red List of Threatened Species 1998. http://dx.doi.org/10.2305/IUCN.UK.1998.RLTS.T32504A9710439.en. Accessed 10 June 2018.

- White F (1983) The Zambezian regional centre of endemism. In: White F (ed) The vegetation of Africa: a descriptive memoir to accompany the UNESCO/AETFAT/UNSO vegetation map of Africa (Natural Resources Research 20). UNESCO, Paris, pp 86-101

CHAPTER 2

POTENTIAL FOR SUSTAINABLE FOREST UTILIZATION IN TANZANIAN COMMUNITY FOREST: ENVIRONMENTAL FACTORS AND WOOD QUALITIES OF AFRICAN BLACKWOOD

African Blackwood (ABW) (*Dalbergia melanoxylon*) mainly occurs in the coastal areas of East Africa, including in Tanzania and Mozambique, and its heartwood is commonly known to be one of the most valuable materials used in the production of musical instruments. Although the heartwood is one of the most expensive timbers in the world, very low material yield has recently resulted in the significant reduction of natural individuals. This might have serious impact on local communities, because this tree is apparently the only species that can support their livelihood. Therefore, a solution to the problem is urgently needed in terms of the sustainable development of communities. In this chapter, chapter 2, the environmental factors (stand structure and soil properties) influencing the tree characteristics of ABW were studied in the Miombo woodlands of southern Tanzania, where ABW was widely distributed. Three community forests located in Kilwa District, Lindi Region, Tanzania, were selected as the survey sites, and 10-13 small plots (0.16 ha/plot) were arbitrary established surrounding ABW at each site. In addition, the stem qualities of standing trees were evaluated by visual inspection rating and a non-destructive measurement of stress-wave velocity, for understanding the relationship between environmental factors and growth form. It was found that ABW was widely distributed under various environmental conditions with intensive population, and that their growth form depended on environmental factors. Since there was no significant difference of stress-wave velocities among the site, our findings suggest that the dynamic properties of ABW trees does not depend on growth conditions, which is generally influenced by various external factors. These results present important information regarding the sustainable forest management of ABW.

2.1 Research objective

The main purpose of this chapter is to assess the potential of the ABW tree in terms of sustainable forest utilization. The relationship between distribution and environmental factors (surrounding vegetation and soil) must be clarified before sustainability of ABW in natural forest can be achieved. Although some difficulties have currently been noted in terms of the economic feasibility of ABW (Gregory *et al.* 1999), forest management focused on this resource could

continuously contribute to the local community forest due to the economical uniqueness of the wood. Therefore, valuable ABW that meets the requirements of musical instruments should be produced effectively by controlling appropriate growth conditions.

In general, the surrounding environment, including climate factors, soil type, and surrounding vegetation, has the potential to influence tree growth. Such environmental conditions have already been studied in some locations (Munishi *et al.* 2007; Munishi *et al.* 2011; Banda *et al.* 2006; Julin *et al.* 1993; Koch *et al.* 2004; Mariki and Wills 2014), however the relationship between environmental conditions and wood quality has not been yet been clarified. In this chapter, some environmental conditions in the natural distribution areas of ABW were compared to determine the relationship between tree growth and wood quality. The results can contribute to establishing the sustainable forest management by local communities.

2.2 Materials and methods

2.2.1 Survey sites

A forest survey was conducted in the southern part of Tanzania, Kilwa District, Lindi Region, which covers 13,347.5 km^2 and is one of Tanzania's most densely forested Districts (Ilunga Muledi *et al.* 2016). More than 150,000 ha of this area has been designated FSC-certified forest supported by MCDI, and it has principally been community forests managed by a local group. Three Forest Stewardship Council (FSC) -certified community forests (Kikole, Nainokwe, and Nanjirinji) were selected as samples (Figs. 2.1, 2.2). In each forest, 9–11 small temporary plots (0.16 ha: 40 m × 40 m) were set using GPS (eTrex, Garmin International Inc., Kansas, USA) and a laser range finder (TruPulse360, Laser Technology, Inc., Colorado, USA). The plots were arbitrary set to evaluate the differences of environmental factors (vegetation and soil) among the sites, around where ABW trees has been standing. A total of 31 plots were set as survey sites: 11 in Kikole and Nainokwe, and 9 in Nanjirinji. Two plots without ABW trees were included at each site as references. The survey was conducted in July and December 2017.

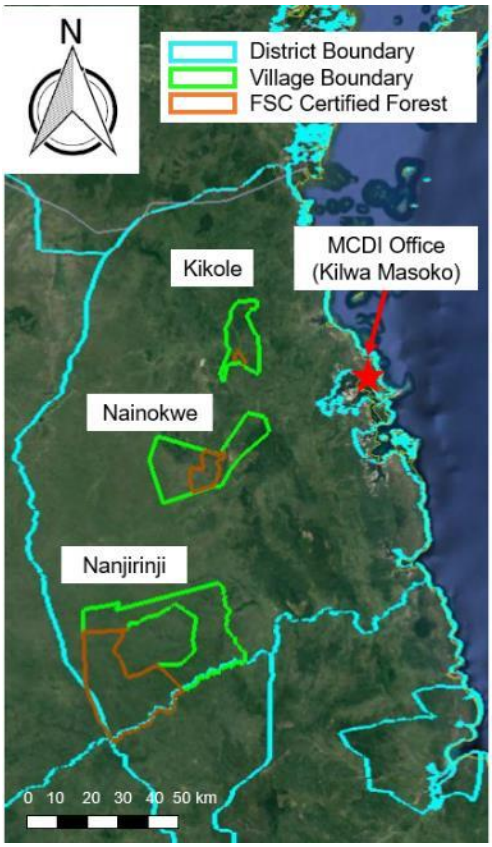


Fig. 2.1 Location map of the survey sites (District Boundary was adapted from The World Bank: https://energydata.info/dataset/tanzania-region-District-boundary-2012, Village Boundary and FSC Certified Forest area were adapted from MCDI: http://www.mpingoconservation.org/where-we-work/on-the-map/).

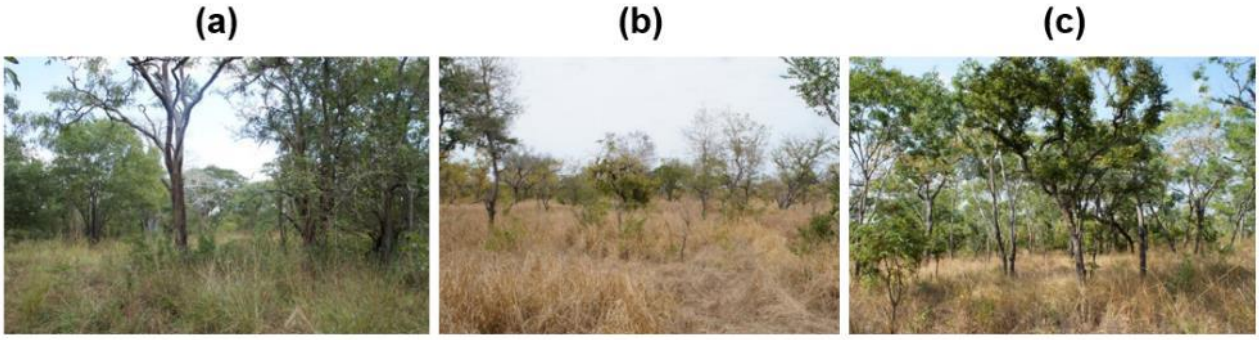


Fig. 2.2 Representative pictures of survey sites: **(a)** Kikole site; **(b)** Nainokwe site; **(c)** Nanjirinji site.

2.2.2 Vegetation survey

All living trees over 10 cm DBH (1.3 m from the ground) were measured for DBH and D10 (diameter at 0.1 m from the ground) using a diameter tape. In the case of multi-stemmed trees less than 1.3 m above the ground, each stem was measured separately, and the biggest DBH stem was regarded as the individual DBH. The number of individuals was also counted in this way. Trees were tagged and classified by local species name. Each scientific name was finally identified as supplemental information referenced by previous survey reports (Gregory *et al.* 1999; Banda *et al.* 2006; Ilunga Muledi *et al.* 2016) (Table 2.1). Furthermore, both tree height and branch height of ABW trees over 10 cm DBH were measured by the above-mentioned laser range finder, to evaluate the growth form of ABW. Total basal area of each tree, *G*, was calculated by the following equation (Eq. 2.1):

$$G = \sum_{k=1}^{n} \left[\pi \left(\frac{D_k}{2} \right)^2 \right] \qquad (2.1)$$

where D_k is the DBH of each tree, and k is the stem number of each tree species.

Table 2.1 Local and scientific names of representative trees in the survey sites (Gregory *et al.* 1999; Banda *et al.* 2006; Ilunga Muledi *et al.* 2016). Some species have not yet been identified. Mchenga in Nainokwe and Mtondoro in Nanjirinji had different local names, but were identified as the same species.

Local Name	Scientific Name	Family
Mpingo	*Dalbergia melanoxylon*	Fabaceae
Mhani	*Brachystegia spp.*	Fabaceae
Miombo	*Brachystegia spiciformis*	Fabaceae
Msolo	*Pseudolachnostylis maprouneifolia*	Phyllanthaceae
Mnepa	*Pteleopsis myrtifolia*	Combretaceae
Mtomoni	*Diplorhynchus condylocarpon*	Apocynaceae
Kingonogo	*Combretum spp.*	Combretaceae
Mpangapanga	*Millettia stuhlmannii*	Fabaceae
Mchenga	*Julbernardia paniculata*	Fabaceae
Mtondoro	*Julbernardia paniculata*	Fabaceae
Msumari	**Not identified**	
Msenjele	*Acacia nigrescens*	Fabaceae
Muhungo	*Acacia robusta*	Fabaceae
Mjare	*Sterculia appendiculata*	Malvaceae
Mtandawara	*Markhamia lutea*	Bignoniaceae
Mlondondo	*Xeroderris stuhlmanii*	Fabaceae

2.2.3 Soil sampling and evaluation

Soil samples were collected from the center of each plot and defined as the equalized condition. At each sampling point, 4 soil cores were collected from 0–10, 45–55, 95–105 and 145–155 cm depth using a soil auger (DIK-100A, Daiki Rika Kogyo Co. Ltd., Saitama, Japan). Soil condition was evaluated in the field by Munsell soil color, finger soil texture, and soil pH (H_2O) measurement by a glass electrode pH meter (pH meter D-51, HORIBA, Kyoto, Japan) with a soil suspension 1 (soil): 2.5 (distilled water) ratio. Soil color was evaluated under sunlight according to the standard Munsell soil color chart, and soil texture was determined by finger test for moist soil samples with reference to the widely used USDA system (Rowell 2014).

2.2.4 Evaluation of surface appearance

The surface appearance of all living ABW trees in each plot over 10 cm DBH was evaluated according to the following criteria with reference to a previous report (Fukuchi *et al.* 2011). The lower part of the stem, from 0.3 m up to 1.3 m, was divided into quarters virtually (Fig. 2.3), and each part was classified into one of 4 grades (0, 1, 2, 3) based on the ratio of clear areas with no visible defects, including cracks, holes, piths, etc. (Table 2.2). The grade of each living tree was obtained using the average of the 4 quarters.

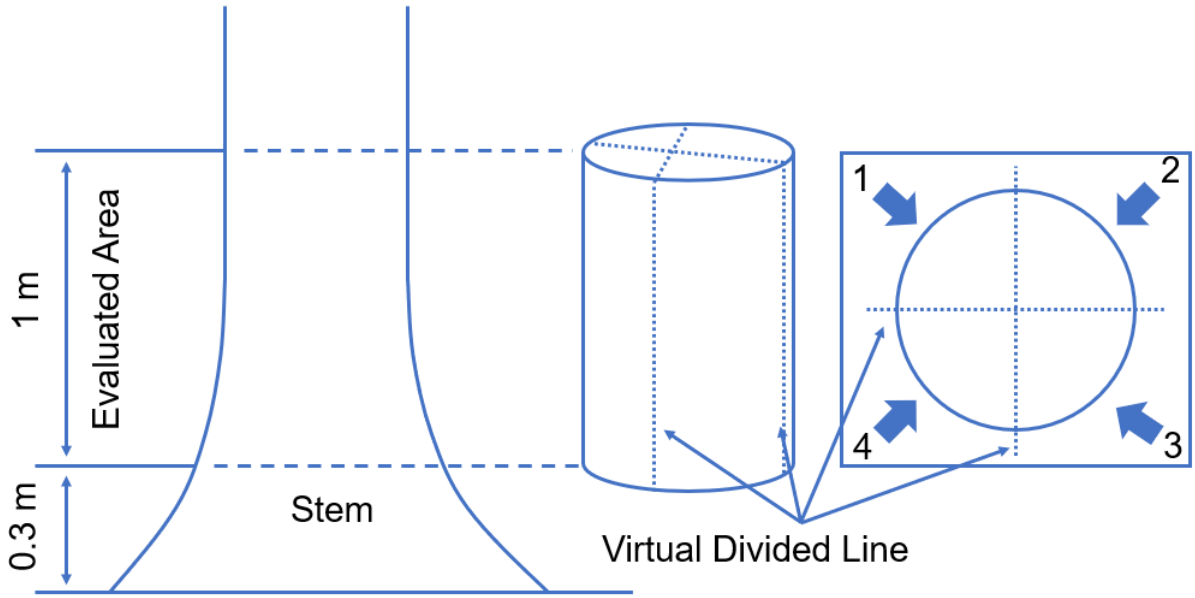


Fig. 2.3 Surface appearance evaluation. The numbers, 1, 2, 3 and 4, indicate the 4 evaluated surfaces on each stem. The average grade of each stem was calculated by all results from every surface.

Table 2.2 Grade list for stem surface evaluation.

Grade	Clear Part of surface	Note (visual standard)
3	> 90 %	Extremely clear, no defects detected in visual inspection
2	60–90 %	Almost clear but some defects detected
1	30–60 %	Some serious defects on limited area of surface
0	0–30 %	Significant serious defects detected on wide area of surface

2.2.5 Measurement of stress-wave velocity

The dynamic physical properties of living ABW trees were evaluated by measuring stress propagation time in trees with a microsecond timer, FAKOPP (FAKOPP Enterprise, Agfalva, Hungary). Stress propagation time is generally related to the dynamic physical properties of materials. In particular, the time in the Longitudinal direction (L-direction) of timbers can be converted to the dynamic Young's modulus using material density. Both start and stop sensors were set on a tree surface at a fixed distance (1 m) at a height of 0.3–1.3 m on the L-direction of the tree. A stress wave was input by a single tap of a specific hammer (Fig. 2.4). Sensors were struck into the bark (2 cm deep) at a 60 degrees angle to the surface (Fig. 2.4). Although the angle for this test is normally 45 degrees (Fujisawa *et al.* 2005), a larger angle was needed in this study due to the significant hardness of ABW. Stress-wave velocity V_s (m/s) was approximately calculated by the following equation (Eq. 2.2):

$$V_s = \frac{L}{T} \qquad (2.2)$$

where L is defined as the distance (1 m) between sensors, and T indicates the average stress propagation time of each tree (12 replications per tree: 3 times per quarter (Fig. 2.3)).

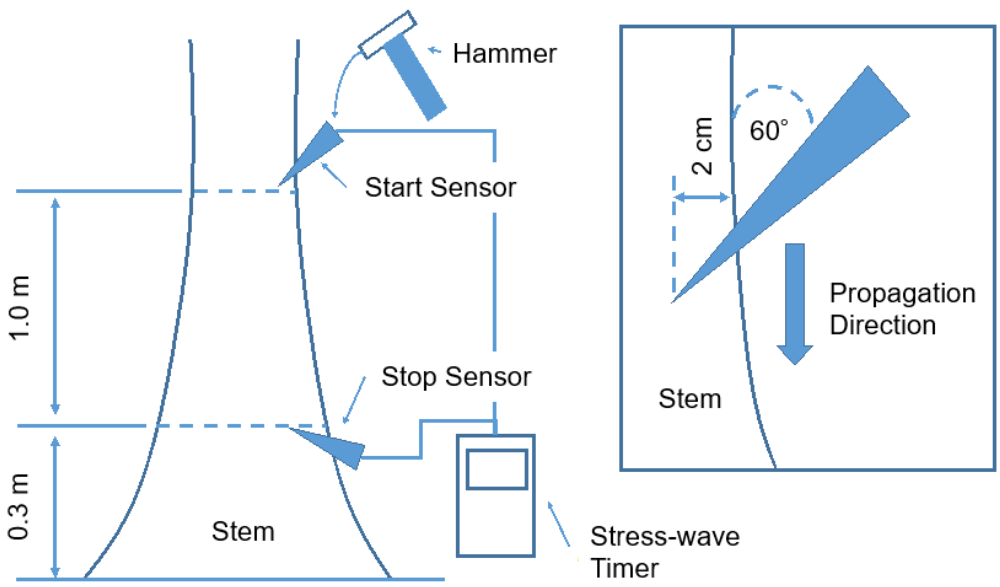


Fig. 2.4 An experimental set-up for measuring stress propagation time using FAKOPP.

2.2.6 Data treatment and statistical analysis

Classification and ordination of tree vegetation data were performed based on total *G* of each species, and tree population of each plot. Tree population was calculated from the number of individuals with the biggest DBH of all stems in the case of multi-stemmed trees. Data items were statistically compared by Kruskal-Wallis test to analyze the relative effect of each factor (BellCurve for Excel, Social Survey Research Information Co. Ltd., Tokyo, Japan). In addition, at 1 % critical difference the Steel-Dwass test was used as a supplementary test. Every referenced plot was analyzed by the same method.

2.3 Results

2.3.1 Tree species composition

Figure 2.5 shows total *G* of all measured trees at each site calculated by Eq. 2.1. The total *G* values of the 3 sites were 15.07 m^2/ha in Kikole, 9.64 m^2/ha in Nainokwe, and 12.66 m^2/ha in Nanjirinji. Nainokwe was the lowest total *G* value, and was separated from those of other 2 sites. The same trend was found at reference plots (Kikole: 4.10 m^2/ha, Nainokwe: 2.66 m^2/ha, Nanjirinji: 3.72 m^2/ha). The average basal area of stands in Nainokwe was also smaller than the other sites, although the difference was not statistically significant at 1 % level (Kikole–Nainokwe: $p = 0.0260$, Nainokwe–Nanjirinji: $p = 0.6045$, Kikole–Nanjirinji: $p = 0.1271$). The tree species diversity was the lowest in Nainokwe where only three dominant species (Mpingo (ABW), Miombo (*Brachystegia spiciformis*) and Msolo (*Pseudolachnostylis maprouneifolia*)) have occupied more than 68 % of total basal area. The *G* values of ABW at the 3 sites were 5.27 m^2/ha in Kikole, 4.19 m^2/ha in Nainokwe, and 5.20 m^2/ha in Nanjirinji. This was equal to *ca.* 35 % of the total *G* value in Kikole, *ca.* 44 % in Nainokwe, and *ca.* 41 % in Nanjirinji (Fig. 2.5).

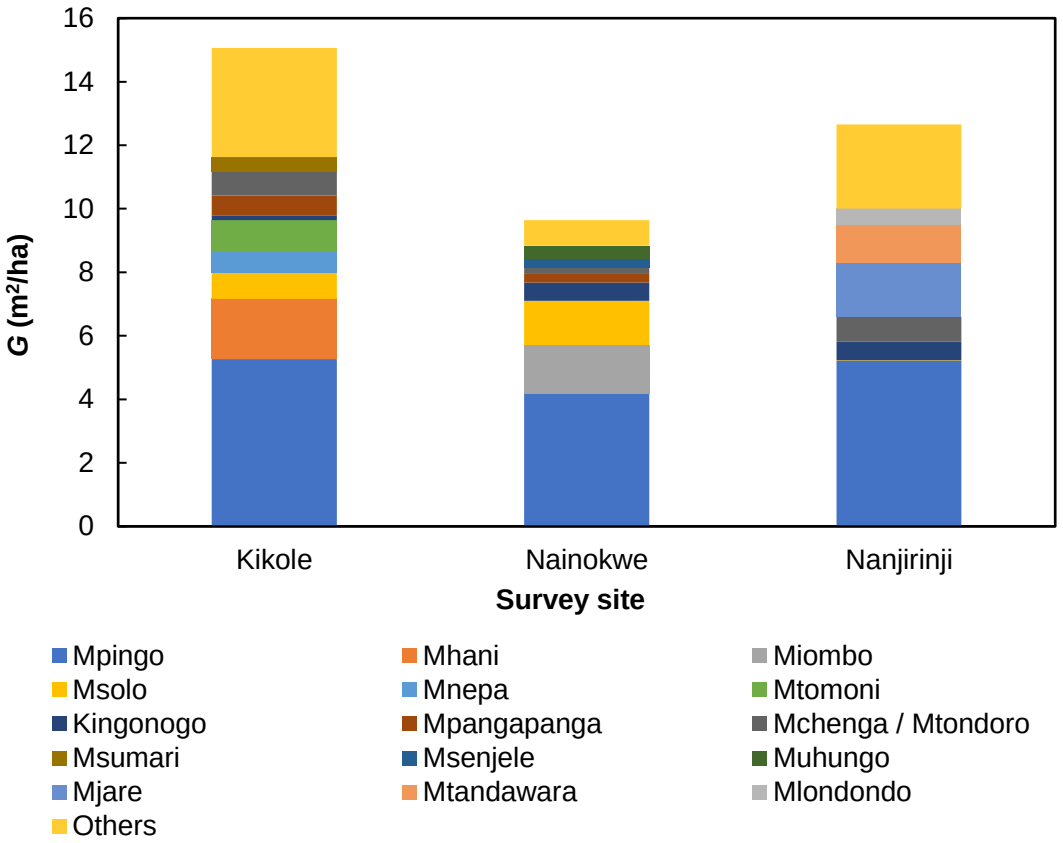


Fig. 2.5 Total G per hectare by species for three survey sites.

As shown in Table 2.3, the population density (number of individual trees/ha) of ABW was highest in Nainokwe (57.39 trees/ha), followed by Kikole (40.01 trees/ha), and Nanjiriji (31.94 trees/ha) (Table 2.3). In addition, the tree density of all species including ABW was also highest in Nainokwe (Table 2.3). The growth form (DBH and tree height) of ABW in Nainokwe was also significantly smaller than at the other sites, whereas DBH of all species in Nainokwe was not statistically different from Nanjirinji (p = 0.6201) (Table 2.3).

Table 2.3 Comparison of specified parameters among 3 sites (ABW: African Blackwood).

Forest	No./ha		DBH (cm)		ABW Height (m)*	ABW Branch Height (m)*
	ABW	All trees	ABW*	All trees*		
Kikole	40.91	159.09	34.87 ± 12.80[b]	33.30 ± 13.28[b]	10.54 ± 3.12[b]	2.32 ± 1.25[b]
Nainokwe	57.39	227.27	24.77 ± 11.91[a]	21.11 ± 10.18[a]	7.25 ± 2.58[a]	1.21 ± 0.59[a]
Nanjirinji	31.94	211.11	36.63 ± 17.16[b]	23.62 ± 16.34[a]	11.01 ± 2.86[b]	1.52 ± 0.60[a]

*Means with the same letter are not significantly different (Steel-Dwass test, $p < 0.01$) following Kruskal-Wallis test.

Distribution of DBH and tree height of ABW trees are shown in Fig. 2.6 and Fig. 2.7, respectively. Nainokwe had an especially high number of small ABW trees (here we defined "small trees" as trees less than 20 cm DBH and 7 m height) (Fig. 2.6). The DBH distribution was quite different between Kikole and Nanjirinji, the number of mid-sized trees (20–40 cm DBH) in Kikole was also relatively larger than that of Nanjirinji, although tree height showed the same trend in both forests (Figs. 2.6 and 2.7). Furthermore, in Kikole and Nainokwe there was a clear tendency of fewer trees with increased DBH, whereas Nanjirinji had a comparatively lower number of mid-sized trees (Fig. 2.6). Some big trees (DBH >50 cm) were observed in all the sites, but there were fewer in Nainokwe (Fig. 2.6). Branch height was lowest in Nainokwe, although the difference was not statistically significant at 1 % level ($p = 0.0474$) (Table 2.3).

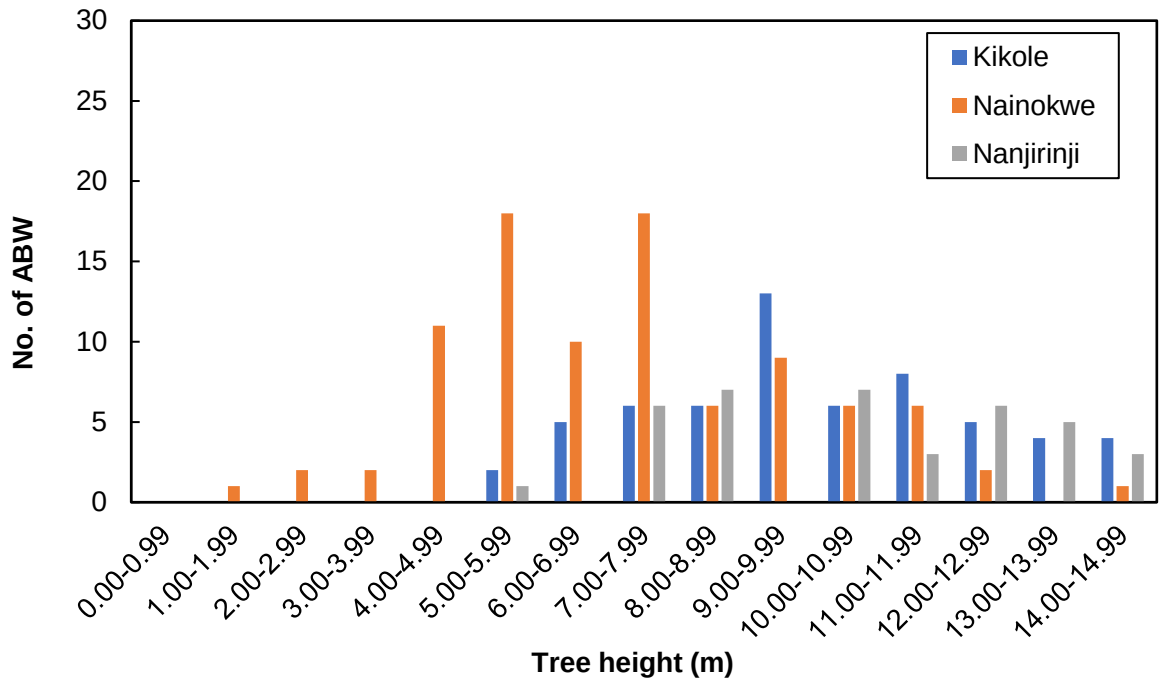


Fig. 2.6 Distribution of DBH at each site (African Blackwood (ABW) only).

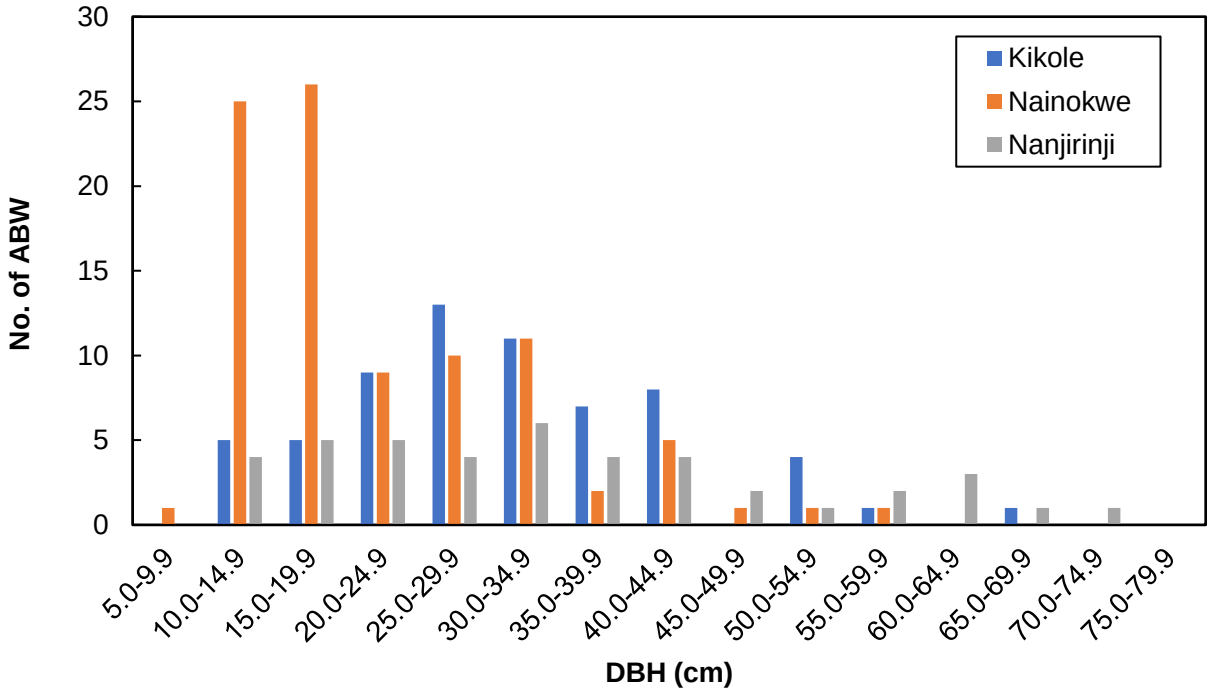


Fig. 2.7 Distribution of tree height at each site (African Blackwood (ABW) only).

Figure 2.8 shows the correlation between DBH and D10 in each site. The average values (mean ± SD) of D10 were 50.38 ± 15.64 cm (Kikole), 39.08 ± 14.60 cm (Nainokwe) and 56.23 ± 24.61 cm (Nanjirinji), respectively. The average value of Nainokwe was significantly lower than the values of other 2 sites at 1 % level, whereas there was no significant difference between Kikole and Nanjirinji at 1 % level. According to the linear regressions of the data plots, the slope of regression line in Nanjirinji was the highest ($y = 0.9048x$, $R^2 = 0.8964$), and the slope of Nainokwe was the lowest of all sites ($y = 0.7619x$, $R^2 = 0.8306$) (Kikole: $y = 0.8257x$, $R^2 = 0.8757$) (Fig. 2.8).

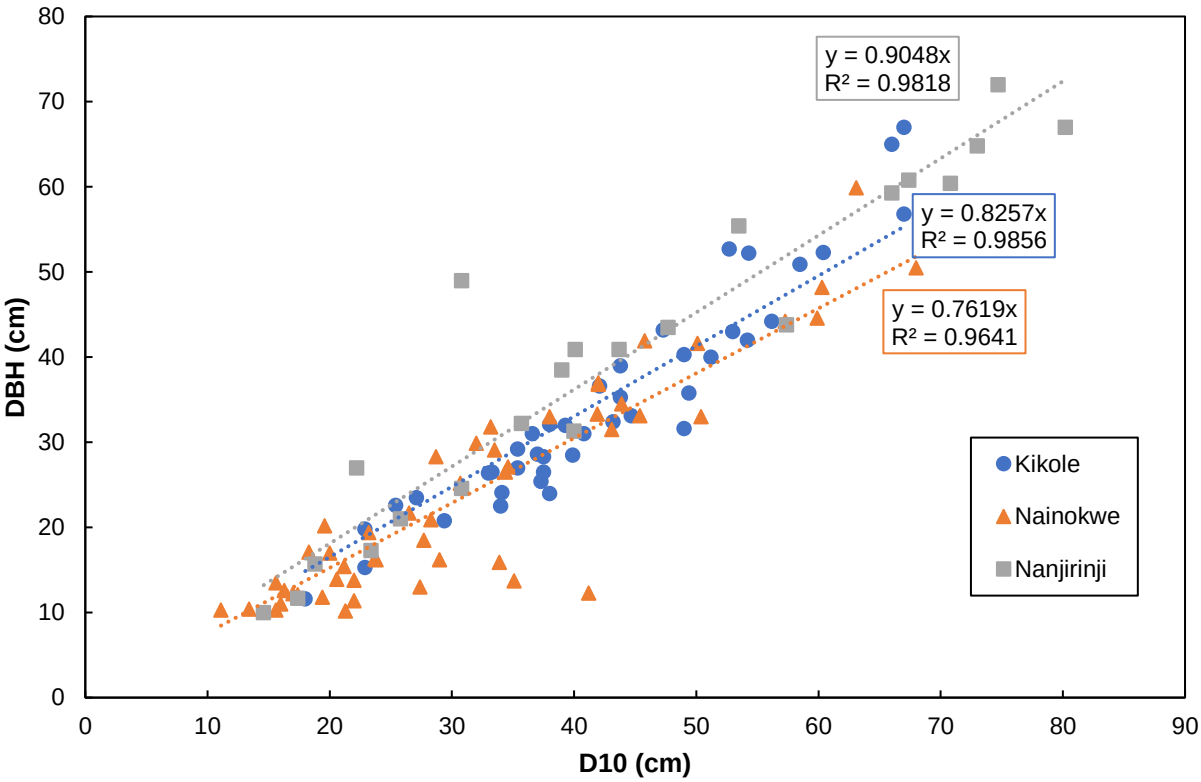


Fig. 2.8 Relationship between DBH and D10 in the survey sites. The dotted line of each color indicates the liner regression of the plots in each site, Blue: Kikole, Orange: Nainokwe, Gray: Nanjirinji.

2.3.2 Soil conditions

Tables 2.4 and 2.5 show soil data for the 3 sites whereby several soil types were observed, depending on the sampling location (depth and plot). The soil of Kikole was most sandy compared to the other 2 sites, with a range from clay loam (CL) to sandy loam (SL) (Tables 2.4 and 2.5). On

the other hand, most of soil samples in Nainokwe and Nanjirinji were evaluated as clay (C), with white crystal-like calcium carbonate (Tables 2.4 and 2.5). There were no significant differences in soil pH (H_2O) between Nainokwe and Nanjirinji, but Kikole was significantly lower than the other sites (Table 2.4). Soils of yellowish to reddish colors (7.5YR–10.0YR in Munsell Color) were recorded for some plots in both Kikole and Nainokwe, whereas mostly dark-colored soil (blackish soil, less than 4.0 in color value) was observed in Nanjirinji. The same trend was also found in the reference plots (Tables 2.4 and 2.5).

Table 2.4 Soil conditions in the 3 survey sites: soil texture, Munsell Color YR (mean ± SD), Color value (mean ± SD) and pH (H_2O) (mean ± SD).

Survey site		n	Major Soil Texture	Munsell Color YR*	Color value*	pH (H_2O)*
Sampling plot	Kikole	44	SL - CL	8.2 ± 1.99[a]	4.7 ± 1.52[b]	6.5 ± 0.98[a]
	Nainokwe	41	L - C	8.1 ± 2.08[a]	3.9 ± 0.72[a]	7.3 ± 1.05[b]
	Nanjirinji	33	C	6.7 ± 1.46[b]	3.1 ± 0.66[a]	7.5 ± 1.01[b]
Referenced plot**	Kikole	8	SL - CL	7.8 ± 0.88	3.9 ± 0.83	6.5 ± 0.64
	Nainokwe	8	LS - C	5.6 ± 1.16	4.1 ± 0.35	6.1 ± 0.84
	Nanjirinji	6	C	6.7 ± 1.30	2.8 ± 0.41	7.2 ± 0.60

*Means with the same letter are not significantly different (Steel-Dwass test; $p < 0.01$) following Kruskal-Wallis test.

**Control plots were not statistically analyzed due to their limited replicates.

Table 2.5 Soil texture data in all the sampling locations (S: Sand, LS: Loamy Sand, SL: Sandy Loam, SCL: Sandy Clay Loam, SC: Sandy Clay, L: Loam, LC: Loamy Clay, CL: Clay Loam, C: Clay) including control plots (plot No. with a small letter, *). a: $CaCO_3$, b: Fe nodules, c: $CaCO_3$ + Fe nodules. 10 cm, 50 cm, 100 cm and 150 cm: sampling depth from the ground level.

Plot No.	Kikole				Plot No.	Nainokwe				Plot No.	Nanjirinji			
	10 cm	50 cm	100 cm	150 cm		10 cm	50 cm	100 cm	150 cm		10 cm	50 cm	100 cm	150 cm
1	C	C	CL	CL	1	LS[a]	SC	SC	SC	1	L	C	C	C
2	CL	SCL	SCL	S	2	LS	C[a]	C[a]	C[a]	2	LS	LS	SL	LS
3	SL	SL	SL	SCL	4	LC	C	C	C	4	C	C	C	
4	LS	LS	LS	LS	5	C	C	C	C	5	C	C	C	SC
5	SL	L	SCL	SL	6	C	C	C[c]	C	7	C	C	C	C
6	LS	SC	C	SCL	7	LC	C	C[c]	-	8	C	C[a]	C[a]	C[a]
7	S	SL	SL	LS	8	LC	C	SC[c]	-	9	SL	SC[a]	C[a]	C[a]
9	L	CL	C	C	9	C	C	C[a]	C	10	SCL	SC[a]	SC[a]	-
10	C	C	C	C	10	LC	C[a]	C[a]	C	11	LS	C	C	-
12	CL	CL	SL	LS	11	CL	C[b]	C[b]	-					
13	LS	SL	CL	SCL	12	CL	C	C	C					
8*	LS	L	SL	LS	3*	LS	CL	C	C	3*	LS	C	-	-
11*	CL	C	C	C	13*	LS	CL	CL	CL	6*	C	C	C	C

2.3.3 Quality analysis of living trees

Evaluation values of the appearance of ABW trees were converted into an average grade: Low: 0.00–0.99, Middle: 1.00–1.99, or High: 2.00–3.00. Figure 2.9 shows the individual occurrence ratio of each grade in the Kikole, Nainokwe and Nanjirinji sites. In Kikole and Nanjirinji, the majority of trees received a “Middle” grade, while Nanjirinji had a larger number of “High” graded trees, over 30 % (Fig. 2.9). On the other hand, most trees in Nainokwe were evaluated as “Low”, and it had a much lower rate of “Middle” and “High” grade trees (Fig. 2.9).

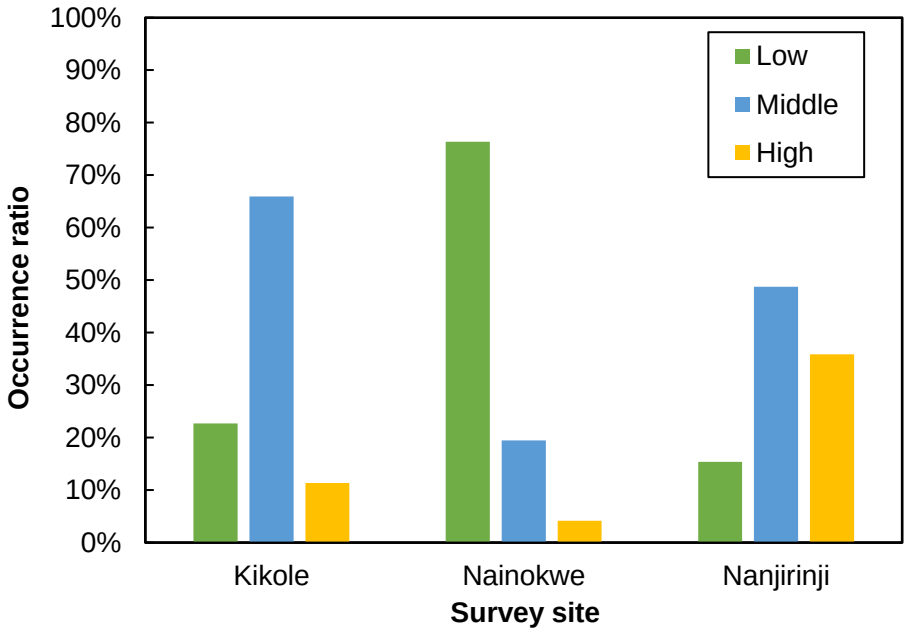


Fig. 2.9 Occurrence ratio of individuals evaluated at each site.

As shown in Table 2.6, average stress-wave velocity (V_s) in Nanjirinji (2990 m/s) was higher than those in the other sites (Kikole: 2808 m/s, Nainokwe: 2676 m/s); V_s in Nainokwe was the lowest value of all sites, and the difference compared to the Nanjirinji site was significant at 1 % level ($p < 0.001$, Table 2.6) although there was no significant difference at 1 % level among survey sites, Kikole and Nainokwe ($p = 0.276$), Kikole and Nanjirinji ($p = 0.241$).

Table 2.6 Average stress-wave velocity (V_s) of African Blackwood (ABW) trees in the survey sites.

Survey site	V_s (m/s)*
Kikole	2808 ± 585[ab]
Nainokwe	2676 ± 409[a]
Nanjirinji	2990 ± 419[b]

*Means with the same letter are not significantly different (Steel-Dwass test; $p < 0.01$) following Kruskal-Wallis test.

When all V_s data of ABW trees was plotted against DBH (Fig. 2.10) and appearance evaluation value (Fig. 2.11), there was interestingly no clear tendency although poor correlation was found

between V_s and appearance grade (V_s–DBH: r = 0.0637, V_s–appearance grade: r = 0.2356). Furthermore, there was no relationship in their parameters of each site (Fig. 2.10, 2.11) even though DBH, height and appearance of trees in Nainokwe was respectively inferior to those of the other 2 sites (Table 2.3). In addition, V_s against each appearance grade was further compared for only over middle grade (1.00–3.00). Poor correlation was shown between all V_s and appearance grades (r = 0.2512), however there was no significant difference at 1 % level among survey sites (Kikole–Nainokwe: p = 0.1666, Nainokwe-Nanjirinji: p = 0.9852, Kikole–Nanjirinji: p = 0.0762).

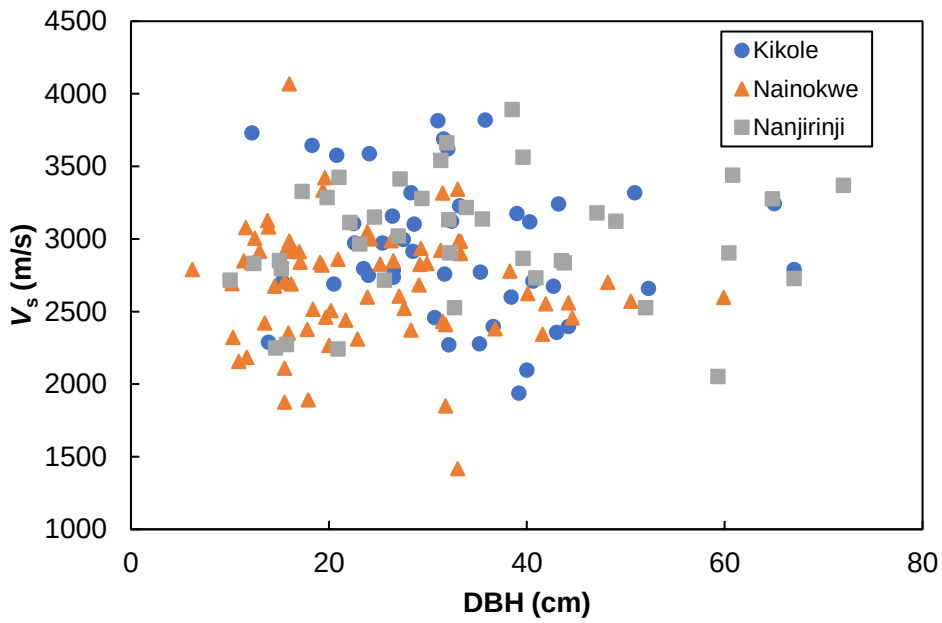


Fig. 2.10 Relationship between DBH and stress-wave velocity (V_s) of African Blackwood (ABW). Each correlation coefficient of the site was respectively showed as follows; Kikole: r = -0.1749; Nainokwe: r = -0.0999; Nanjirinji: r = 0.1134.

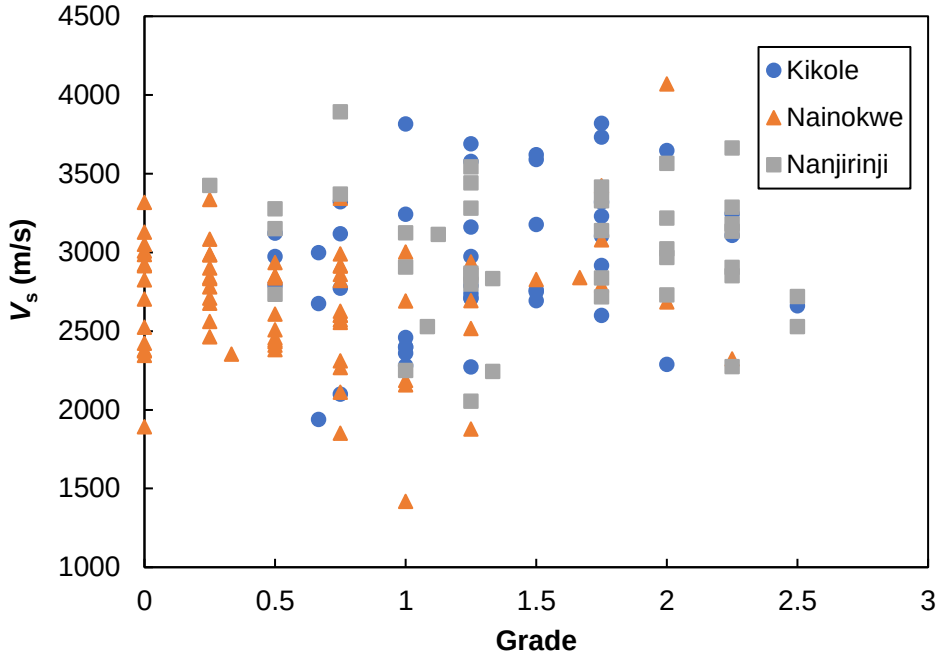


Fig. 2.11 Relationship between the evaluated appearance grade and stress-wave velocity (V_s) of African Blackwood (ABW). Each correlation coefficient of the site was respectively showed as follows; Kikole: r = 0.2622, Nainokwe: r = 0.0523, Nanjirinji: r = -0.1128.

2.4 Discussion

In this survey, it was found that ABW could survive under various environment conditions with high relative dominance. Different vegetation types were observed depending on the sample location (Fig. 2.5), and the vegetation surrounding ABW tree location significantly influenced the tree growth. Nainokwe was significantly different from the 2 other sites in terms of tree species composition and growth form (Fig. 2.5, Table 2.3). Nainokwe is mainly covered by wooded grassland, while open woodland covers larger areas of Kikole (Mariki and Wills 2014). Meanwhile, Nanjirinji could also be categorized into mostly open woodland because of its statistical similarity to the parameters of Kikole, although there have not yet been any official reports (Table 2.3, Fig. 2.5, 2.6, 2.7).

Generally, there are many low trees with lower branch height in wooded grassland compared to open woodland (Mariki and Wills 2014) (Table 2.3, Fig. 2.7). In particular, some ABW trees in Nainokwe showed relatively small DBH in conjunction with tree height compared to those of other sites (Table 2.3, Fig. 2.6). This forest had many juvenile ABW trees with small DBH and low

height (Fig. 2.6, 2.7). Furthermore, the correlation between DBH and D10 as shown in Fig. 2.8 indicated that many trees were multi-stemmed in this forest. Although the average D10 in this forest was the lowest of all sites, the D10 of trees under 20 cm DBH tended to be larger than those of other sites (Fig. 2.8). This suggests that many juvenile stems possibly regenerate from one root, the regenerated stems grow with smaller DBH in wooded grassland. Considering the diagnostic parameters listed in Table 2.3 and Table 2.6, it seems that environmental impacts from forest parameters continuously influenced growth conditions.

On the other hand, the DBH of all trees in Kikole site were significantly bigger than those of the other sites, with an intensive number of mid-sized ABW trees, quite different from the Nanjirinji (Table 2.3, Fig. 2.6). This suggests that there might be a relationship between forest density and ABW regeneration. ABW has been known as a light-demanding species, thus it might not regenerate under heavy closed vegetation (Orwa *et al.* 1994; Washa 2008; Ball *et al.* 1998). In cases where the forest density is lower, ABW trees can also become multi-stemmed with smaller DBH and lower height as shown in Nainokwe (Fig. 2.6, 2.7, 2.8, Table 2.3). This is generally known as a typical physiological response. Trees in dense forests must compete for light, which places a premium on height growth, meaning that trees grow tall (Koch *et al.* 2004). It was suggested that the significant difference of DBH distribution between Nainokwe and other sites was a result of the natural ABW habitat. Kikole site apparently has the appropriate conditions under which ABW trees can coexist with other species because many trees with larger growth form were observed with high population density of ABW (Table 2.3).

Forest conditions including vegetation type generally depend on environmental factors such as topography, climate, and human activities. Tree growth can be especially impacted by topography, resource availability and previous disturbance (Julin *et al.* 1993; Koch *et al.* 2004). The abundance, distribution, and diversity of vegetation tend to be strongly influenced by the qualities of physical landscape, with plant species arising from both physical and chemical characteristics of the land (Munishi *et al.* 2011). Luoga *et al.* (2004) reported that harvesting activity significantly affects the vegetation structure of woodlands, and the specific distribution of aged trees might be the result of clear-cutting of such trees (Jew *et al.* 2016). Banda *et al.* (2006) also reported that the gradient of land protection has been predicted to influence forest ecosystems in terms of growth form, regeneration, and species richness. As a result, some potential factors, including human activities such as fire, harvesting, *etc*., have not yet been studied here. Further

investigation should be conducted in terms of vegetation transition by human activities to clarify the specific distribution of ABW trees in natural forest.

Ilunga Muledi *et al.* (2016) reported a variety of soil factors in a miombo woodland, and that vegetation was related to soil factors. In this chapter study, we found a variety of soil types at the 3 sites: from sandy to clay, and with or without $CaCO_3$ and/or Fe nodules (Table 2.4, 2.5). However, the results clearly suggest that ABW can grow in a wide variety of soil types regardless of their properties. Also, in this survey, dark-colored soils from CL to C soil texture observed in some plots in the Nanjirinji (Table 2.5), which might have better physical (better drainage and water-retention) and better chemical (more nutrients) properties.

In general, soil color depends on major inorganic components and the amount of organic matter, which determines the physical properties of the top soil. High clay content results in a high capacity for stocking organic matter, so that soil color darkens. Heavier clayey alkali-soil with high $CaCO_3$ content seems to affect root extension into deeper soil layers. In contrast, sandy soil (S), which was frequently observed in Kikole, might have disadvantages for plant growth due to poor nutrients and low water holding capacity. The soils of Nainokwe were similar to Nanjirinji, although their vegetation obviously differed. It was concluded that ABW trees could grow under a variety of soil types, and even where other plants cannot grow well. It has been suggested that rooting of ABW trees is not affected greatly by the soil condition due to their coexistence with mycorrhizal fungi, which fixes nitrogen and is commonly known to radiate out 30–50 m by root suckers (Washa 2008, Washa *et al.* 2012). The survival of ABW was apparently the result of adaptation to a wide variety of soil conditions despite their less-competitive behavior in high-diversity dense forest.

Recently, studies of the relationship between tree growth and V_s have reported that stress-wave velocity depends on planting density, which also influenced tree-form properties such as bending, multi-stems, cracks, decay, etc. (Fukuchi *et al.* 2011). A positive relationship was observed between MOE and V_s of the living coniferous tree, Hinoki (*Chamaecyparis obtusa* Endle.) (Fujisawa *et al*. 2005; Ikeda and Arima 2000; Ishiguri *et al.* 2006), and another positive relationship between wood hardness and V_s has been observed by using a stress wave timer in some tropical hardwoods (*Nectandra cuspidata*, *Mezilaurus itauba* and *Ocotea guianensis*) (Da Silva *et al.* 2014). In addition, V_s, wood density and ultrasonic velocity which is another non-destructive measurement has also positively related to MOE of some planted hardwood trees (*Melia azedarch*, *Shorea* spp. and *Maesopsis eminii*) (Van Duong and Matsumura 2018; Karlinasari *et al.* 2018).

Although wood density of the measured trees has not been evaluated in this study, the significant difference of wood density might result in the different V_s as shown in such current studies for other species. Wood density is an important parameter to understand wood physical properties, thus evaluation of wood density should be needed for further discussing tree growth and wood quality. In addition, V_s is affected by defects such as cracks and pith including holes, because the stress-wave principally selects the shortest internal propagation route. Therefore, propagation time would be delayed by the existence of any serious defects between sensors. However, the physical properties of obtained ABW might not significantly be related to appearance conditions in this study, because there were only poor correlations between V_s and the appearance grades (Fig. 2.11). V_s was also poorly correlated with appearance grades even in case of further analysis for only over middle grades.

ABW trees in Nainokwe site obviously had a worse appearance than the other 2 sites with the lower parameters in this survey (Fig. 2.9, Table 2.3). This might have been due to the co-relationship between environmental conditions and tree growth, although their growth rate have not completely evaluated yet. Trees on fertile, well-drained soils such as loam can grow rapidly, thus resulting in high density forest (Mariki and Wills 2014), but promoting fluting (Julin *et al.* 1993). Fluting severity has been positively correlated with tree growth and branch height in Western Hemlock trees (*Tsuga heterophylla*) (Singleton *et al.* 2003). Furthermore, disturbances such as clear-cutting and mechanical stress can also induce more fluting (Julin *et al.* 1993). Karlinasari *et al.* (2018) also showed the negative correlations between wood quality traits (wood density, dynamic MOE and ultrasonic velocity) and tree volume at the planting sites of same aged trees. Since the stress-wave velocities (V_s) were not significantly different among survey sites with a variety of soil/landscape conditions (Table 2.6, Fig. 2.10, 2.11), the findings in this survey suggest that the dynamic physical properties of ABW trees are not related to growth conditions in the natural forest, which is generally influenced by various external factors.

2.5 Conclusions

In this chapter, both the environmental conditions and physical properties of living ABW trees were investigated to figure out the appropriate conditions for growth and quality requirements as musical instruments. ABW can survive under various environmental conditions with intensive population. However, the trees living under inferior conditions in wooded grassland (Nainokwe) tended to have smaller DBH, lower height, and worse appearance. By contrast, the trees in open

woodland, Kikole and Nanjirinji, showed better qualities in tree form and appearance. Especially, the trees tended to have larger DBH, higher height, and better appearance in Nanjirinji site where the soils with better properties were mostly observed. This suggested that soil condition could influence ABW growth. The difference of ABW growth form might be related to the light-demanding, and the influence of the struggle against other plant species. There was no significant difference in stress-wave velocities of living ABW trees obtained from all 3 sites, even though tree appearance was observed to be affected by the surrounding environment. Therefore, it was concluded that there was no significant effect of external factors on the real physical properties of trees as timber materials. Forest management should focus on producing high-yield ABW trees with bigger DBH and higher branch height to achieve sustainable industrial use. Moreover, methods to promote the growth process while maintaining original specifications (*i.e.*, dark-colored heartwood, high density) are needed in natural forest. Sustainable and healthy forest should be based on sustainable wood utilization.

As mentioned earlier, ABW is an endangered species, and thus plantations with proper management must be undertaken in near future, together with novel approaches for the effective utilization of currently unused parts of the trees. The wood flow forming studied in Chapter 3 was expected to become a solution to improve the current usage of ABW. The results obtained in this chapter may contribute significantly to the sustainable production and utilization of this precious timber resource.

2.6 References

- Ball SMJ (2004) Stocks and exploitation of East African Blackwood *Dalbergia melanoxylon*: a flagship species for Tanzania's miombo woodlands? *Oryx* 38(3): 266-272. DOI:10.1017/S0030605304000493

- Ball SMJ, Smith AS, Keylock NS, Manoko L, Mlay D, Morgan ER, Ormand JRH, Timothy J (1998) Tanzanian Mpingo ‘96 Final Report. Mpingo Conservation Project, Fauna & Flora International, Cambridge

- Banda T, Schwartz MW, Caro T (2006) Woody vegetation structure and composition along a protection gradient in a miombo ecosystem of western Tanzania. *Forest Ecology and Management* 230(1-3): 179-185. DOI:10.1016/j.foreco.2006.04.032

- Boutin H, Le Conte S, Vaiedelich S, Fabre B, Le Carrou JL (2017) Acoustic dissipation in wooden pipes of different species used in wind instrument making: an experimental study. *The Journal of the Acoustical Society of America* 141(4): 2840-2848. DOI:10.1121/1.4981119

- Brémaud I, El Kaïm Y, Guibal D, Minato K, Thibaut B, Gril J (2012) Characterization and categorization of the diversity in viscoelastic vibrational properties between 98 wood types. *Annals of Forest Science* 69(3): 373-386. DOI:10.1007/s13595-011-0166-z

- Bryce JM (1967) The commercial Timbers of Tanzania. Forest Division, Ministry of Agriculture & Co-operatives, Moshi, Tanzania

- Burkill HM (1995) Useful plants of west tropical Africa, vol. 3. Royal Botanic Gardens Kew, London

- Campbell B, Frost P, Byron N (1996) Miombo woodlands and their use: overview and key issues. In: Campbell B (ed) The Miombo in Transition: woodlands and welfare in Africa, Center for International Forestry Research (CIFOR), Bogor, pp 1-10

- Campbell BM, Angelsen A, Cunningham A, Katerere Y, Sitoe A, Wunder S (2007) Miombo woodlands: Opportunities and barriers to sustainable forest management. Harare. Centre for International Forestry Research (CIFOR), Bogor

- Christian MY, Chirwa PW, Ham C (2008) The influence of tourism on the woodcarving trade around Cape Town and implications for forest resources in southern Africa. *Development Southern Africa* 25(5): 577-588. DOI:10.1080/03768350802447800

- Cunningham AB, Manalil S, Flower K (2015) More than a music tree: 4400 years of *Dalbergia melanoxylon* trade in Africa. *South African Journal of Botany* 98: 167. DOI:10.1016/j.sajb.2015.03.004

- Da Silva F, Higuchi N, Nascimento CC, Matos JLM, de Paula EVCM, dos Santos J (2014) Nondestructive evaluation of hardness in tropical wood. *Journal of Tropical Forest Science* 26(1): 69-74

- Desanker PV, Frost PGH, Justice CO, Scholes RJ (eds) (1997) The miombo network: framework for a terrestrial transect study of land-use and land-cover change in the miombo ecosystems of central Africa. IGBP Report 41, The International Geosphere-Biosphere Programme (IGBP), Stockholm

- Fukuchi S, Yoshida S, Mizoue N, Murakami T, Kajisa T, Ohta T, Nagashima K (2011) Analysis of the planting density toward low-cost forestry: a result from the experimental plots of Obi-sugi planting density **(in Japanese)**. *Nihon Ringakkai Shi/Journal of the Japanese Forestry Society* 93(6): 303-308

- Fujisawa Y, Kashiwagi M, Inoue Y, Kuramoto N, Hiraoka Y (2005) An application of FAKOPP to measure the modulus of stem elasticity of hinoki (*Chamaecyparis obtusa* Endl.) **(in Japanese)**. *Kyushu Journal of Forest Research* 58: 142-143

- Gregory A, Ball SMJ, Eziefula UE (1999) Tanzanian Mpingo 98 Full Report. Mpingo Conservation Project, Tanzania

- Hamisy WC, Hantula J (2002) Characterization of genetic variation in African Blackwood, *Dalbergia melanoxylon* using random amplified microsatellite (RAMS) method. Plant genetic resources and biotechnology in Tanzania, Part 1: biotechnology and social aspects. In: Proceedings of the second national workshop on plant genetic resources and biotechnology, Arusha, Tanzania, 6–10 May 2002.

- Ikeda K, Arima T (2000) Quality evaluation of standing trees by a stress-wave propagation method and its application II: evaluation of sugi stands and application to production of sugi (*Cryptomeria japonica* D. Don) structural square sawn timber **(in Japanese)**. *Mokuzai Gakkaishi* 46(3): 189-196

- Ilunga Muledi, J, Bauman D, Drouet T, Vleminckx J, Jacobs A, Lejoly J, Meerts P, Shutcha MN (2016) Fine-scale habitats influence tree species assemblage in a miombo forest. *Journal of Plant Ecology* 10(6): 958-969. DOI:10.1093/jpe/rtw104

- Ishiguri F, Kawashima M, Iizuka K, Yokota S, Yoshizawa N (2006) Relationship between stress-wave velocity of standing tree and wood quality in 27-year-old Hinoki (Chamaecyparis obtusa Endl.) **(in Japanese)**. *Journal of the Society of Material Science* 55(6): 576-582

- Jenkins M, Oldfield S, Aylett T (2002) International trade in African Blackwood. Fauna & Flora International, Cambridge

- Jew EK, Dougill AJ, Sallu SM, O'Connell J, Benton TG (2016) Miombo woodland under threat: consequences for tree diversity and carbon storage. *Forest Ecology and Management* 361: 144-153. DOI: 10.1016/j.foreco.2015.11.011

- Julin KR, Shaw CG, Farr WA, Hinckley TM (1993) The fluted western hemlock of Alaska II: Stand observations and synthesis. *Forest Ecology and Management* 60(1-2): 133-141. DOI:10.1016/0378-1127(93)90027-K.

- Karlinasari L, Andini S, Worabai D, Pamungkas P, Budi SW, Siregar IZ (2018) Tree growth performance and estimation of wood quality in plantation trials for *Maesopsis eminii* and *Shorea* spp.. *Journal of Forestry Research* 29(4): 1157-1166. DOI:10.1007/s11676-017-0510-8

- Khatun K, Corbera E, Ball S (2017) Fire is REDD+: offsetting carbon through early burning activities in south-eastern Tanzania. *Oryx* 51(1): 43-52. DOI:10.1017/S0030605316000090

- Koch GW, Sillett SC, Jennings GM, Davis SD (2004) The limits to tree height. *Nature* 428(6985): 851

- Lemmens RHMJ (2008) *Dalbergia melanoxylon* Guill. & Perr. In: Louppe D, Oteng-Amoako AA, Brink M (eds) Plant Resources of Tropical Africa. Available via DIALOG. https://uses.plantnet-project.org/en/Dalbergia_melanoxylon_(PROTA). Accessed 25 November 2017

- Lovett J (1987) Mpingo – the African Blackwood. *Swara* 10: 27-28

- Luoga EJ, Witkowski ETF, Balkwill K (2004) Regeneration by coppicing (resprouting) of miombo (African savanna) trees in relation to land use. *Forest Ecology and Management* 189(1-3): 23-35. DOI:10.1016/j.foreco.2003.02.001

- Malimbwi RE, Luoga EJ (2000) Prevalence and standing volume of Dalbergia melanoxylon in coastal and inland sites of southern Tanzania. *Journal of Tropical Forest Science* 12(2): 336-347

- Mariki AS, Wills AR (2014) Environmental factors affecting timber quality of African Blackwood (*Dalbergia melanoxylon*). Mpingo Conservation & Development Initiative, Tanzania

- Mbuya LP, Msanga, HP, Ruffo CK, Birnie A, Tengnas BO (1994) Useful trees and shrubs for Tanzania: identification, propagation and management for agricultural and pastoral communities. Regional Soil Conservation Unit, Swedish International Development Authority, Nairobi, Kenya.

- Millington AC, Chritchley RW, Douglas TD, Ryan P (1994) Prioritization of indigenous fruit tree species based on formers evaluation criteria: some preliminary results from central region, Malawi. In: Proceedings of the regional conference on indigenous fruit trees of the Miombo ecozone of Southern Africa, Mangochi, Malawi, 23-27 January 1994

- Miya M, Ball SMJ, Nelson FD (2012) Drivers of deforestation and forest degradation in Kilwa District. Mpingo Conservation & Development Initiative, Tanzania: 1-34

- Munishi PKT, Shear TH, Wentworth T, Temu RAPC (2007) Compositional gradients of plant communities in submontane rainforests of eastern Tanzania. *Journal of Tropical Forest Science* 19: 35-45

- Munishi PKT, Temu RAPC, Soka G (2011) Plant communities and tree species associations in a Miombo ecosystem in the Lake Rukwa basin, Southern Tanzania: Implications for conservation. *Journal of Ecology and the Natural Environment* 3(2): 63-71

- Nshubemuki L, Mugasha AG (1995) Chance Discoveries and Germ-plasm Conservation in Tanzania: Some Observations on 'Reserved' Trees. *Environmental Conservation* 22(1): 51-55. DOI:10.1017/S037689290003407X

- Orwa C, Mutua A, Kindt R, Jamnadass R, Simons A (1994) Agroforestry Database: A tree species reference and selection guide version 4.0, World Agroforestry Centre ICRAF, Nairobi, KE. http://www.worldagroforestry.org/sites/treebs/treedatabases.asp. Accessed 25 January 2017

- Rowell DL (2014) Soils in the field. In: Rowell DL (ed) Soil science: Methods & applications. Longman Group, London, pp 1-16. DOI:10.4324/9781315844855

- Sacandé M, Vautier H, Sanon M, Schmit L (eds) (2007) *Dalbergia melanoxylon* Guill. & Perr. *Seed Leaflet* 135

- Singleton R, DeBell DS, Marshall DD, Gartner BL (2003) Eccentricity and fluting in young growth western hemlock in Oregon. *Western Journal of Applied Forestry* 18(4): 221-228

- Sproβman R, Zauer M, Wagenfur A (2017) Characterization of acoustic and mechanical properties of common tropical woods used in classical guitars. *Results in Physics* 7: 1737-1742. DOI:10.1016/j.rinp.2017.05.006

- URT (United Republic of Tanzania) (2007) Prime Minister's Office, Information about Lindi region, Kilwa District. http://lindi.go.tz/limdi/limdi-rural/. Accessed 1 May 2018

- UNEP-WCMC (2017) Review of selected *Dalbergia* species and *Guibourtia demeusei*. UNEP-WCMC, Cambridge

- Van Duong D, Matsumura J (2018) Within-stem variations in mechanical properties of *Melia azedarach* planted in northern Vietnam. Journal of Wood Science 64: 329-337. DOI:10.1007/s10086-018-1725-9

- Washa BW (2008) Dependence of Dalbergia melanoxylon Natural Populations on Root Suckers Germination. *Journal of Asian and African Studies* 24(32): 177-198

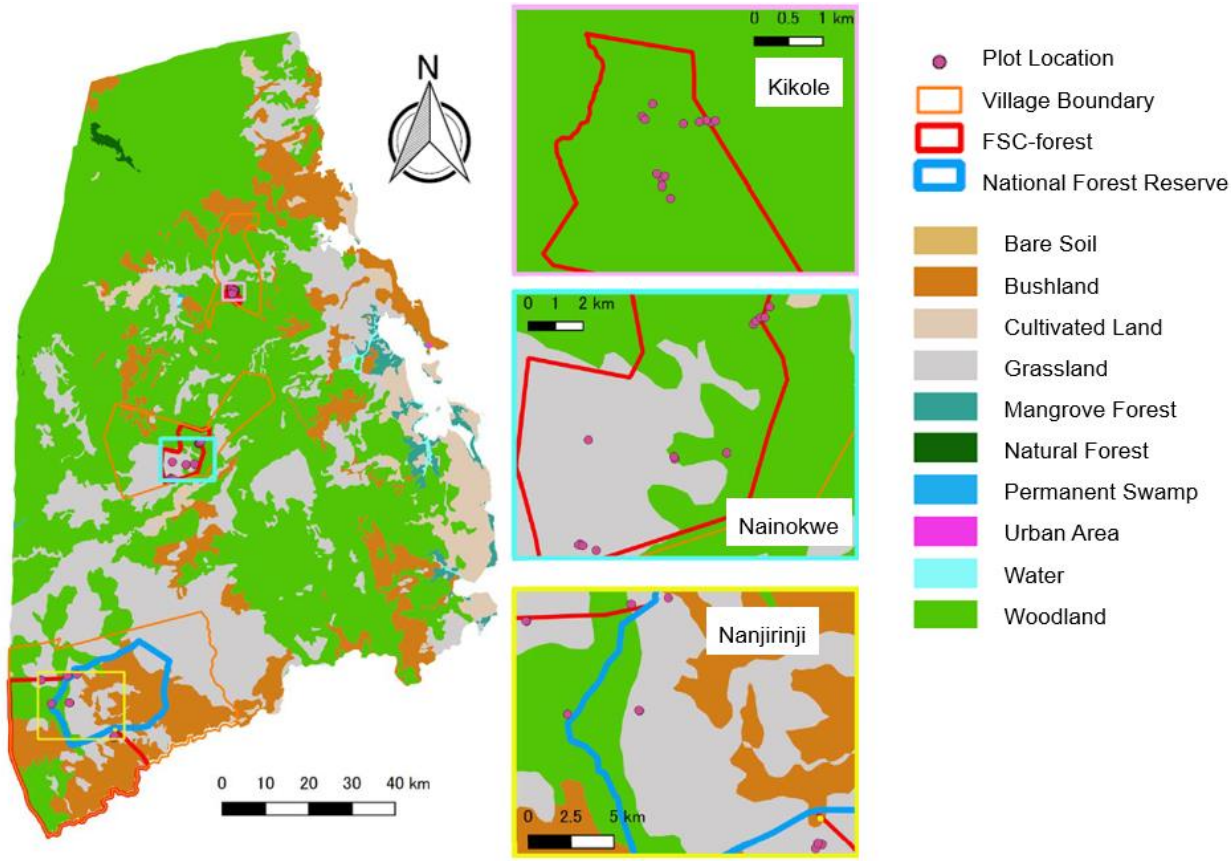
- Washa BW, Nyomora AMS, Lyaruu HMV (2012) Improving propagation success of *D. melanoxylon* (African Blackwood) in Tanzania (II): rooting ability of stem and root cuttings of *Dalbergia melanoxylon* (African Blackwood) in response to rooting media sterilization in Tanzania. *Tanzania Journal of Science* 38(1): 43-53

- White F (1983) The Zambezian regional centre of endemism. In: White F (ed) The vegetation of Africa: a descriptive memoir to accompany the UNESCO/AETFAT/UNSO vegetation map of Africa (Natural Resources Research 20). UNESCO, Paris, pp 86-101

- World Conservation Monitoring Centre (1998) *Dalbergia melanoxylon*. The IUCN Red List of Threatened Species 1998. DOI: 10.2305/IUCN.UK.1998.RLTS.T32504A9710439.en. Accessed 10 June 2018

2.7 Appendices

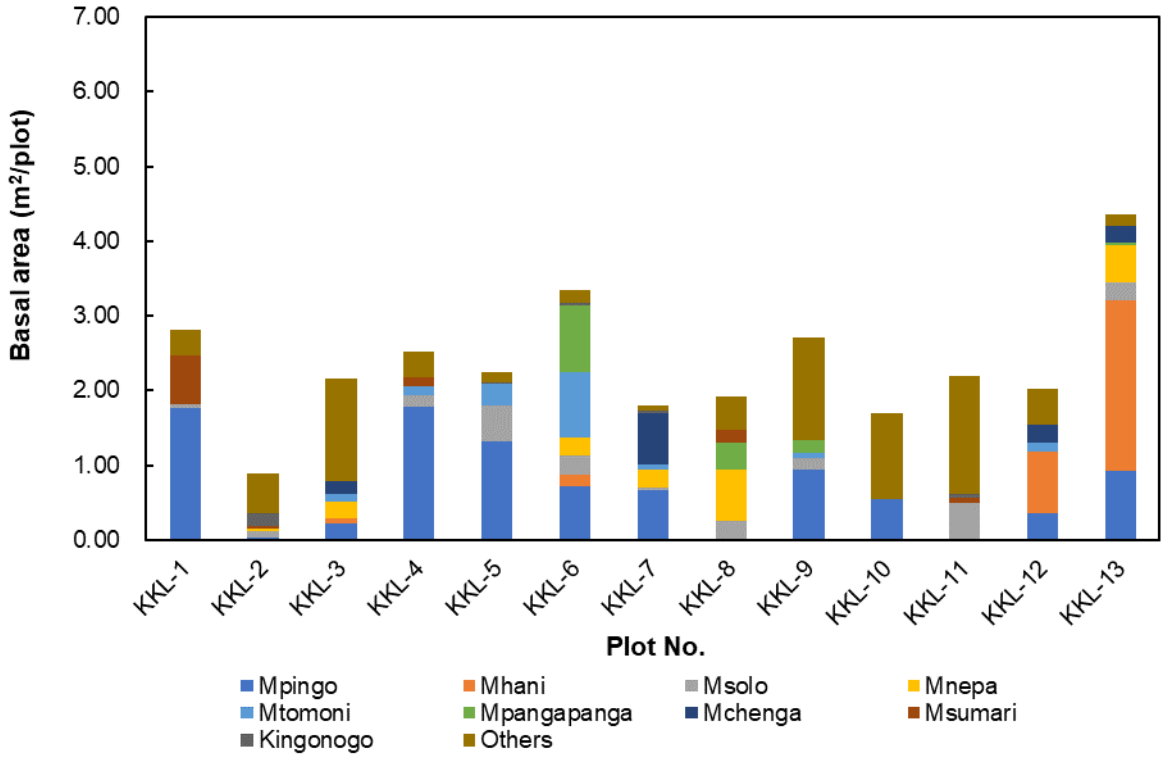
Appendix 2.1 Plot Locations in the land use map of Lindi Region.



Note: Land use map was adapted from diva-GIS: http://www.diva-gis.org/datadown, Village Boundary and FSC Forest area were adapted from MCDI: http://www.mpingoconservation.org/where-we-work/on-the-map/.

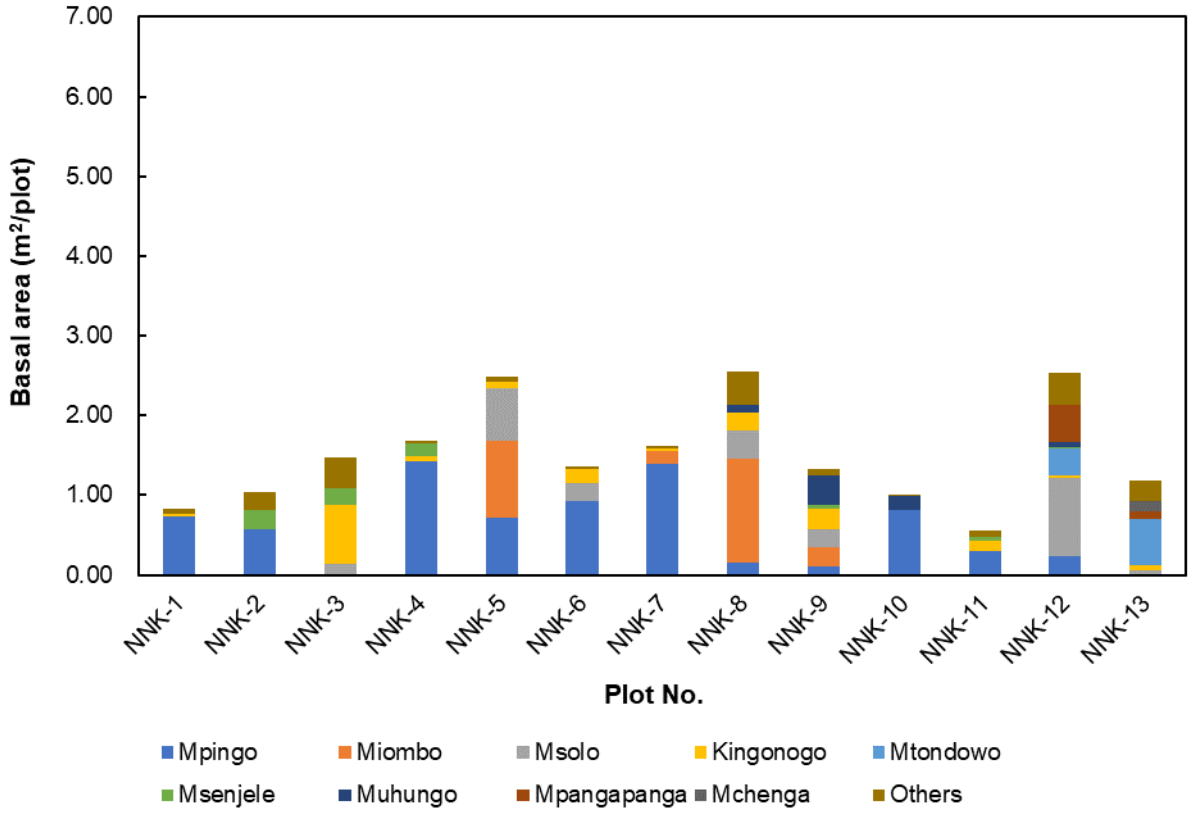
Appendix 2.2 Basal area of each plot in Kikole site (m^2/plot).

Local Name	KKL -1	KKL -2	KKL -3	KKL -4	KKL -5	KKL -6	KKL -7	KKL -8	KKL -9	KKL-10	KKL-11	KKL-12	KKL-13	Total
Mpingo	1.76	0.02	0.21	1.79	1.32	0.72	0.66	0.00	0.95	0.54	0.00	0.36	0.92	9.28
Mhani	0.00	0.00	0.08	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.81	2.28	3.32
Msolo	0.05	0.09	0.00	0.15	0.48	0.26	0.04	0.26	0.15	0.00	0.50	0.00	0.25	2.22
Mnepa	0.00	0.04	0.22	0.00	0.00	0.24	0.24	0.69	0.00	0.00	0.00	0.00	0.50	1.93
Mtomoni	0.00	0.00	0.10	0.12	0.29	0.86	0.07	0.00	0.08	0.00	0.00	0.13	0.00	1.67
Mpangapanga	0.00	0.00	0.00	0.00	0.00	0.90	0.00	0.36	0.17	0.00	0.00	0.00	0.04	1.47
Mchenga	0.00	0.00	0.16	0.00	0.00	0.00	0.69	0.00	0.00	0.00	0.00	0.24	0.22	1.31
Msumari	0.66	0.04	0.00	0.11	0.00	0.00	0.00	0.17	0.00	0.00	0.06	0.00	0.00	1.03
Kingonogo	0.00	0.17	0.00	0.00	0.02	0.03	0.04	0.00	0.00	0.00	0.05	0.00	0.00	0.31
Others	0.34	0.53	1.37	0.34	0.13	0.17	0.06	0.44	1.36	1.15	1.58	0.47	0.14	8.08
Total	2.81	0.89	2.15	2.51	2.24	3.34	1.79	1.91	2.70	1.69	2.19	2.02	4.35	



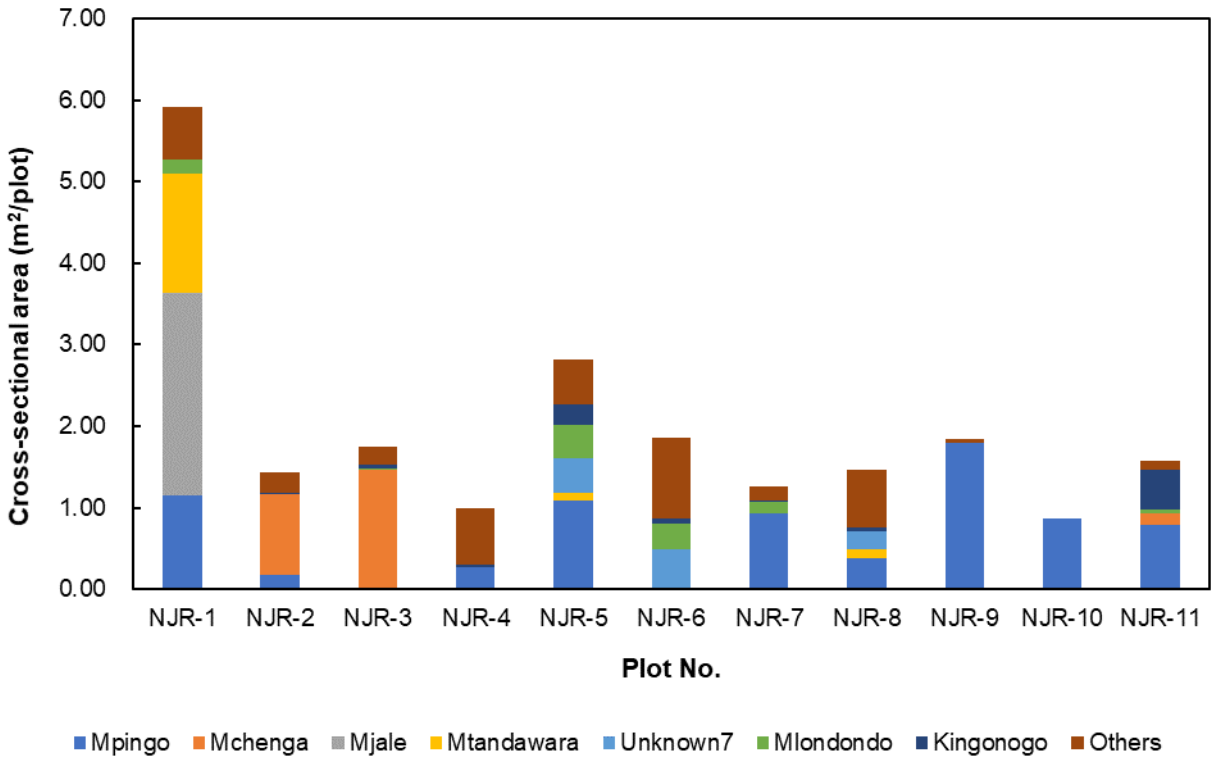
Appendix 2.3 Basal area of each plot in Nainokwe site (m^2/plot).

Local Name	NNK -1	NNK -2	NNK -3	NNK -4	NNK -5	NNK -6	NNK -7	NNK -8	NNK -9	NNK -10	NNK -11	NNK -12	NNK -13	Total
Mpingo	0.74	0.57	0.00	1.42	0.71	0.92	1.40	0.15	0.10	0.82	0.30	0.24	0.00	7.38
Miombo	0.00	0.00	0.00	0.00	0.97	0.00	0.15	1.30	0.24	0.00	0.00	0.00	0.00	2.67
Msolo	0.00	0.00	0.14	0.00	0.66	0.23	0.00	0.36	0.23	0.00	0.00	0.97	0.05	2.64
Kingonogo	0.03	0.00	0.74	0.06	0.08	0.17	0.04	0.23	0.25	0.00	0.13	0.04	0.07	1.83
Mtondowo	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.34	0.57	0.91
Msenjele	0.00	0.24	0.21	0.16	0.00	0.00	0.00	0.00	0.05	0.00	0.05	0.01	0.00	0.72
Muhungo	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.38	0.17	0.00	0.06	0.00	0.71
Mpangapanga	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.47	0.11	0.58
Mchenga	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.13
Others	0.07	0.22	0.39	0.04	0.06	0.03	0.02	0.42	0.07	0.01	0.07	0.41	0.26	2.07
Total	0.83	1.03	1.47	1.69	2.48	1.35	1.61	2.55	1.33	1.00	0.55	2.54	1.18	



Appendix 2.4 Basal area of each plot in Nanjirinji site (m^2/plot).

Local Name	NJR-1	NJR-2	NJR-3	NJR-4	NJR-5	NJR-6	NJR-7	NJR-8	NJR-9	NJR-10	NJR-11	Total
Mpingo	1.16	0.18	0.00	0.28	1.09	0.00	0.93	0.38	1.80	0.87	0.79	7.49
Mchenga	0.00	0.99	1.47	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14	2.60
Mjale	2.47	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.47
Mtandawara	1.47	0.00	0.00	0.00	0.10	0.00	0.00	0.11	0.00	0.00	0.00	1.68
Unknown7	0.00	0.00	0.00	0.00	0.42	0.49	0.00	0.22	0.00	0.00	0.00	1.13
Mlondondo	0.17	0.00	0.01	0.00	0.42	0.31	0.14	0.00	0.00	0.00	0.04	1.08
Kingonogo	0.00	0.02	0.04	0.03	0.24	0.07	0.02	0.04	0.00	0.00	0.49	0.96
Msolo	0.00	0.03	0.07	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.15
Others	0.64	0.25	0.23	0.69	0.56	0.98	0.18	0.71	0.03	0.00	0.11	4.38
Total	5.91	1.47	1.82	1.00	2.82	1.90	1.27	1.46	1.84	0.87	1.58	



Appendix 2.5 Soil color data of Kikole site.

Plot No.	Soil Color (Munsell)				Soil Color (common)			
	10cm	**50cm**	**100cm**	**150cm**	**10cm**	**50cm**	**100cm**	**150cm**
KKL -1	7.5YR2/2	7.5YR3/2	7.5YR4/6	10YR4/6	brownish black	brownish black	brown	brown
KKL -2	10YR5/2	2.5YR7/3	2.5YR7/3	2.5YR7/3	grayish yellow brown	pale reddish orange	pale reddish orange	pale reddish orange
KKL -3	7.5YR4/2	7.5YR4/4	7.5YR4/4	7.5YR4/4	grayish brown	brown	brown	brown
KKL -4	10YR5/4	10YR7/3	10YR6/3	10YR6/4	dull yellowish brown	dull yellow orange	dull yellowish orange	dull yellow brown
KKL -5	7.5YR3/2	10YR4/4	10YR4/4	10YR6/4	brownish black	brown	brown	dull yellow brown
KKL -6	10YR4/2	10YR5/3	10YR7/3	10YR6/6	grayish yellow brown	dull yellowish brown	dull yellowish orange	dull yellow brown
KKL -7	7.5YR5/3	7.5YR4/3	7.5YR3/4	7.5YR4/4	dull brown	brown	dark brown	brown
KKL -8	10YR5/2	7.5YR4/2	7.5YR4/3	7.5YR5/4	grayish yellow brown	grayish brown	brown	dull brown
KKL -9	10YR2/2	7.5YR3/2	7.5YR4/3	7.5YR4/3	brownish black	brownish black	brown	brown
KKL -10	7.5YR3/2	10YR4/2	10YR7/4	10YR7/6	brownish black	grayish yellow brown	dull yellowish orange	bright yellow brown
KKL -11	7.5YR3/1	7.5YR3/1	7.5YR3/1	7.5YR4/2	brownish black	brownish black	brownish black	grayish brown
KKL -12	7.5YR4/2	7.5YR6/4	10YR7/6	10YR7/4	grayish brown	dull orange	bright yellow brown	dull yellow brown
KKL -13	7.5YR3/2	7.5YR4/3	7.5YR3/3	7.5YR4/3	brownish black	brown	dark brown	brown

Appendix 2.6 Soil color data of Nainokwe site.

Plot No.	Soil Color (Munsell)				Soil Color (common)			
	10cm	**50cm**	**100cm**	**150cm**	**10cm**	**50cm**	**100cm**	**150cm**
NNK-1	7.5YR3/2	7.5YR3/3	10YR4/4	10YR4/4	brownish black	dark brown	brown	brown
NNK-2	10YR3/2	10YR3/2	10YR4/2	10YR4/2	brownish black	brownish black	grayish yellow brown	grayish yellow brown
NNK-3	7.5YR4/3	5YR4/4	5YR4/3	5YR4/3	brown	dull reddish brown	dull reddish brown	dull reddish brown
NNK-4	10YR3/2	10YR3/1	10YR4/1	10YR4/2	brownish black	brownish black	brownish gray	grayish yellow brown
NNK-5	7.5YR4/2	10YR4/3	10YR4/4	10YR4/4	grayish brown	dull yelowish brown	brown	brown
NNK-6	7.5YR3/2	5YR4/4	5YR4/6	7.5YR4/6	brownish black	dull reddish brown	reddish brown	brown
NNK-7	7.5YR3/2	5YR4/4	5YR4/3	-	brownish black	dull reddish brown	dull reddish brown	-
NNK-8	5YR3/2	5YR4/4	5YR5/3	-	dark reddish brown	dull reddish brown	dull reddish brown	-
NNK-9	5YR4/1	10YR4/2	10YR5/2	10YR6/3	brownish gray	grayish yellow brown	grayish yellow brown	dull yellow orange
NNK-10	10YR4/2	10YR5/2	10YR4/2	10YR4/3	grayish yellow brown	grayish yellow brown	grayish yellow brown	dull yellowish brown
NNK-11	7.5YR3/2	7.5YR4/4	7.5YR5/4	-	brownish black	brown	dull brown	-
NNK-12	7.5YR3/2	5YR4/4	7.5YR5/3	5YR5/3	brownish black	dull reddish brown	dull brown	dull reddish brown
NNK-13	7.5YR4/3	5YR5/4	5YR4/4	5YR4/6	brown	dull reddish brown	dull reddish brown	reddish brown

Appendix 2.7 Soil color data of Nanjirinji site.

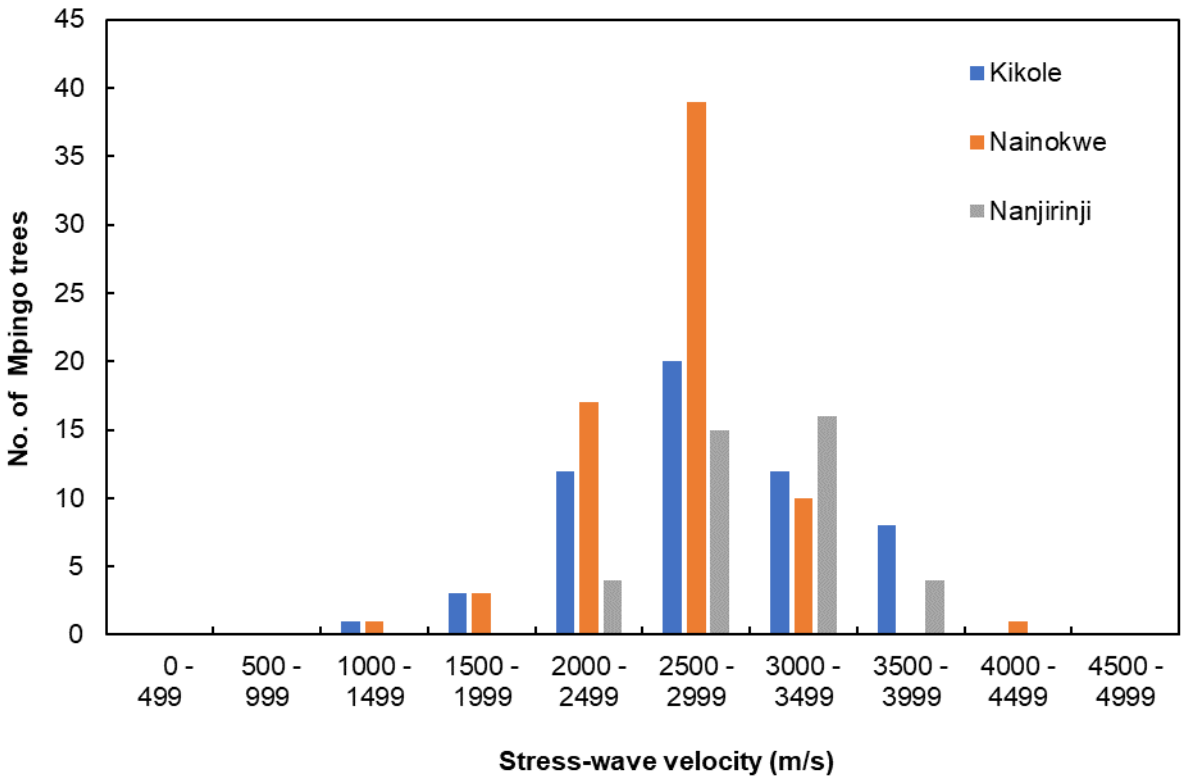
Plot No.	Soil Color (Munsell)				Soil Color (common)			
	10cm	**50cm**	**100cm**	**150cm**	**10cm**	**50cm**	**100cm**	**150cm**
NJR-1	7.5YR2/1	7.5YR2/2	7.5YR3/2	7.5YR3/2	black	brownish black	brownish black	brownish black
NJR-2	7.5YR3/1	7.5YR4/4	5YR4/4	7.5YR4/2	brownish black	dark brown	dull reddish brown	grayish brown
NJR-3	5YR2/2	5YR3/4	-	-	brownish black	dark reddish brown	-	-
NJR-4	7.5YR3/3	5YR3/6	2.5YR3/6	-	dark brown	dark reddish brown	dark reddish brown	-
NJR-5	7.5YR2/1	7.5YR3/2	7.5YR3/2	7.5YR3/2	black	brownish black	brownish black	brownish black
NJR-6	7.5YR3/1	7.5YR3/1	7.5YR3/1	7.5YR3/2	brownish black	brownish black	brownish black	brownish black
NJR-7	7.5YR2/1	7.5YR3/1	7.5YR3/2	7.5YR3/2	black	brownish black	brownish black	brownish black
NJR-8	5YR2/1	5YR3/1	7.5YR3/2	10YR3/2	brownish black	brownish black	brownish black	brownish black
NJR-9	7.5YR2/2	7.5YR3/3	5YR4/4	5YR4/4	brownish black	dark brown	dull reddish brown	dull reddish brown
NJR-10	7.5YR3/2	7.5YR4/2	7.5YR4/3	-	brownish black	grayish brown	brown	-
NJR-11	5YR3/3	5YR4/6	5YR3/6	-	dark reddish brown	reddish brown	dark reddish brown	-

Appendix 2.8 Soil pH (H_2O) and topographic information of all the plots.

Plot No.	Soil pH (H_2O)				Topographic Information
	10cm	50cm	100cm	150cm	
KKL-1	6.71	6.64	6.75	6.86	Lower gentle convex slope
KKL-2	6.71	7.13	8.17	7.94	Lower gentle concave slope
KKL-3	6.09	5.74	5.74	5.77	Flat crest
KKL-4	6.99	7.77	7.88	8.30	Lower gentle convex slope
KKL-5	6.42	5.90	5.92	6.34	Mid gentle simple slope
KKL-6	6.22	8.15	8.18	8.00	Mid gentle concave slope
KKL-7	6.01	5.76	5.67	5.65	Gently convex crest
KKL-8	6.51	6.09	6.40	6.02	Flat crest
KKL-9	6.69	6.84	5.34	5.85	Mid gentle concave slope
KKL-10	6.19	7.23	7.78	7.97	Upper gentle simple slope
KKL-11	6.61	5.81	7.04	7.79	Mid gentle simple slope
KKL-12	6.49	4.96	5.69	6.02	Lower gentle simple slope
KKL-13	6.27	5.23	4.99	5.00	Mid gentle simple slope
NNK-1	6.73	6.36	8.87	8.89	Flat terrain
NNK-2	6.93	8.65	8.55	8.61	Flat terrain
NNK-3	6.64	5.82	5.84	7.99	Flat terrain (small gentle hill)
NNK-4	6.87	7.96	8.40	8.60	Flat terrain (many cracks on surface)
NNK-5	7.04	6.89	7.12	7.14	Flat terrain
NNK-6	6.65	6.65	6.87	7.20	Flat terrain
NNK-7	6.86	6.83	7.87	-	Flat terrain
NNK-8	6.60	6.29	7.76	-	Flat terrain
NNK-9	6.31	7.26	8.04	8.13	Flat terrain
NNK-10	6.74	8.83	9.13	8.92	Flat terrain
NNK-11	6.24	6.83	7.19	-	Flat terrain
NNK-12	5.31	5.54	5.38	5.79	Flat terrain
NNK-13	5.62	5.72	5.56	5.56	Flat terrain
NJR-1	6.94	7.09	7.61	8.35	Lower gentle simple slope
NJR-2	6.80	6.85	6.96	6.97	Mid gentle simple slope
NJR-3	7.14	6.86	-	-	Convex broad ridge
NJR-4	6.45	6.60	6.85	-	Mid gentle simple slope

NJR-5	7.04	6.39	6.80	7.06	Flat terrain
NJR-6	6.40	7.07	7.88	7.94	Flat terrain, well drained
NJR-7	6.39	7.85	8.14	8.41	Flat terrain
NJR-8	6.77	6.33	6.71	7.18	Flat terrain
NJR-9	7.08	9.35	9.50	9.48	Flat terrain
NJR-10	8.39	9.39	9.40	-	Flat terrain
NJR-11	7.04	6.60	7.30	-	Flat terrain

Appendix 2.9 Distribution of stress-wave velocity in Mpingo trees among the survey sites.



Appendix 2.10 Moisture content of a green African Blackwood (ABW) heartwood obtained in Nanjirinji site.

A) Materials and Method

1. Green ABW heartwood

At the harvesting process of ABW, two off-cut logs (150–180 mm, diameter; 1000–1200 mm, length) were obtained from a harvested standing ABW tree. The obtained off-cutting logs were directly carried to the local sawmill factory in the morning of harvesting date, and the specimens (30 mm (L) × 50 mm (R) × 50 mm (T)) of ABW heartwood were processed from each log with 6 replicates: 3 specimens from the middle part, 3 specimens from the edge part.

2. Measurement of moisture content

The weight of specimens (W_1) was measured with the electric scale, and they were oven-dried at 105°C for over 5 days until when the weight change rate in a range of under 1%. The oven-dried weight (W_0) were measured with the electric scale after drying, the moisture content (MC) was calculated using the following equation:

$$\mathrm{MC} = \frac{W_1 - W_0}{W_0} \times 100\ (\%)$$

B) Results (only Table)

Log number	Specimens	Sampling part	MC (%)	Mean ± SD (%)
1	1	Middle of log	21.49	21.91 ± 0.36
	2		22.12	
	3		22.10	
	4	Edge of log	20.13	20.28 ± 0.13
	5		20.39	
	6		20.31	
2	1	Middle of log	21.00	20.88 ± 0.19
	2		20.98	
	3		20.66	
	4	Edge of log	21.83	23.17 ± 1.18
	5		23.64	
	6		24.04	

CHAPTER 3

IMPROVEMENT OF CURRENT AFRICAN BLACKWOOD USAGE: APPLICATION OF WOOD FLOW FORMING

African Blackwood (ABW: *Dalbergia melanoxylon*) has been mainly utilized as an irreplaceable material in musical instruments, *e.g.*, clarinet, oboe and piccolo. Since its use is generally for the production of musical instruments only, most of the harvested volume is wasted due to defects that would affect the quality of final products. Such inefficient usage has resulted in frequent overharvesting, furthermore the local benefit created through log harvesting tend to become much lower than the market value of the timbers. In Chapter 2, it was suggested that ABW could survive under various environmental conditions together with the potential to produce high-yield ABW trees. The usage should be improved to achieve sustainable resource utilization, especially for valuable resources required long-term for growing up to the harvestable sized trees.

Wood flow forming can transform bulk woods into materials in temperature/pressure-controlled mold *via* plastic flow deformation. The main object of this study was to evaluate the deformation characteristics of ABW heartwood test the potential of wasted ABW parts in terms of effective material use. The deformation characteristics of heartwood were examined by free compression tests. Specimens were compressed along the radial direction at 120 °C, and air-dried heartwood was dramatically deformed in the tangential direction. The plastic flow deformation of ABW was amplified by the presence of both extractives and moisture. In particular, the ethanol/benzene (1:2, v/v) soluble extractives in heartwood may have contributed to flow deformation. The results of the dynamic mechanical analysis showed that the air-dried heartwood exhibited softening in a temperature range over 50 °C. The ethanol/benzene soluble extractives contributed to the softening behavior. The clarified deformation characteristics of ABW can contribute to more efficient material use of local forests.

3.1 Research background and objective

The usage efficiency of ABW tends to be inferior to other general hardwood species due to the growth characteristics studied in Chapter 2. Wood flow forming is a novel technique for molding three-dimensional products from bulk wood (Yamashita *et al.* 2007). It has been suggested that wood flow deformation is plastic flow deformation due to the slipping of wood cells in or

around the intercellular layers under specific temperatures (Miki *et al.* 2014). Plastic flow deformation occurs under high compressive load after two types of compressive deformation stages: elastic deformation and densification deformation (Miki *et al.* 2014; Sugino *et al.* 2020). The bulk wood of air-dried Japanese cedar (*Cryptomeria japonica*) was deformed and flowed in a mold by the addition of both high pressure and high temperature, *i.e.*, 150 kN loading at 130 ºC (Yamashita *et al.* 2009). Furthermore, flow deformation could be promoted by increasing moisture content and/or adding thermosetting polymers (Yamashita *et al.* 2009; Miki *et al.* 2013; Miki *et al.* 2014; Seki *et al.* 2017). In particular, it has been suggested that an increase in the polymer content can dramatically improve flow deformation (Seki *et al.* 2016a; Seki *et al.* 2016b). Timber impregnated with polymer can flow based on the thermal softening behavior of the polymer.

The quantity of extractives in ABW heartwood has been estimated to be over 15 wt% in ethanol/benzene (1:2 v/v) solvent extraction, which is much higher than in other *Dalbergia* species, such as *Dalbergia cultrate* and *Dalbergia latifolia* (Yin *et al.* 2018). As described in the next chapter, the quantity of extractives in ABW heartwood was also much higher than other representative Fabaceae species (see Chapter 4). The high concentrated extractives potentially work to promote flow deformation by heating beyond the thermal softening point of them. Although identification and isolation of extractives obtained from ABW heartwood have been partly reported (Eyton *et al.* 1967; Donnelly *et al.* 1969; Seshadri 1972; Yin *et al.* 2018), there is little information about the effect of extractives on the thermal behavior of ABW.

The main objective of this chapter was to reveal the deformation characteristics of ABW, and to discuss the relationship between flow deformation of heartwood and thermal behavior of extractives. Free compression tests were conducted to examine the deformation characteristics of ABW. In addition, the thermal behavior of extractives was evaluated based on the temperature-dependence of the dynamic viscoelasticity of ABW in the modulus of transverse elasticity. The heartwood which occupies the large part of ABW trees was the main target, so that the results might contribute to improvement of the general material utilization of ABW.

3.2Materials and methods

3.2.1 Wood specimens

Specimens of ABW were obtained from logs over 24 cm in diameter at breast height, harvested in 2018 at the Forest Stewardship Council (FSC)-certified forest located in the Kilwa

District, Lindi Region, Tanzania. Two types of specimens were prepared for this study. Disk-shaped specimens of ABW heartwood obtained from tangential sections of the wood with 15-mm diameter (longitudinal, L × tangential, T) and 2-mm thick in the radial direction were prepared for the free compression test with 20 replicates. Rectangular specimens of ABW (heartwood and sapwood), measuring 30 mm (L; longitudinal direction) × 1 mm (R; radial direction) × 5 mm (T; tangential direction), were prepared for the dynamic mechanical analysis with 15 replicates per specimen. All specimens were cut from air-dried timber conditioned for over 3 months at room temperature, and specimens were kept in a controlled chamber (KCL-2000, Tokyo Rikakikai Co. Ltd., Tokyo, Japan) conditioned at 22 ± 2 °C and 60 % relative humidity (RH) for over 30 days.

3.2.2 Pretreatment prior to the tests

Figures 3.1a and 3.1b show the experimental procedures for the disk-shaped and rectangular specimens, respectively. For both, four types of treatment (air-drying (AD), water extraction (WT), ethanol/benzene extraction (EB), and oven-drying (OD)), were prepared with 5 replicates according to the experimental procedures (Fig. 3.1a, 3.1b). All specimens were oven-dried at 105 °C for over 24 h, and their oven-dried weights (W_0) were measured with an electronic scale (GH-252, A&D Company Ltd., Tokyo, Japan).

The extraction processes were applied for the WT and EB specimens (Fig. 3.1). Water extraction was performed as follows. Oven-dried specimens were soaked in 150 mL of distilled water using a sealed Erlenmeyer flask. The soaked specimens were stirred for 10 min. in the water bath at 40 °C with ultrasonic treatment (Branson 5510JDTH, Yamato Scientific Co., Ltd., Tokyo, Japan), and then kept in the controlled chamber at 45 ± 5 °C for 48 h. For the extraction, specimens from different sampling parts (heartwood, sapwood) were placed in different flasks to prevent the migration of extractives between parts. For the EB specimens, extraction was performed in the same way using an ethanol/benzene (1:2, v/v) solution instead of distilled water.

After extraction, both the WT and EB specimens were stored at room temperature for over 1 week, and then oven-dried at 105 °C for over 24 h to measure the extracted weight (W_e) with the electric scale (Fig. 3.1a, 3.1b). The extraction rate was calculated by equation 3.1 using W_0 and W_e:

$$\text{Extraction rate} = \frac{W_0 - W_e}{W_0} \times 100\ (\%) \qquad (3.1)$$

The AD and extracted WT and EB specimens were conditioned at 22 ± 2 °C and 60 % RH for over 3 weeks. The conditioned weight (W_1) was then measured with the electric scale. In addition, the dimensions of each specimen were measured after the conditioning process, as described later. The moisture content (MC) of each specimen was calculated before the tests using the following equations 3.2a and 3.2b:

$$\mathrm{MC} = \frac{W_1 - W_0}{W_0} \times 100\ (\%) \tag{3.2a}$$

$$\mathrm{MC} = \frac{W_1 - W_\mathrm{e}}{W_\mathrm{e}} \times 100\ (\%) \tag{3.2b}$$

The MC of AD specimens was calculated using Eq. 3.2a, while that of extracted specimens (WT and EB) was calculated using Eq. 3.2b.

The dimensions of AD, WT, EB, and OD specimen were measured just before the tests (Fig. 3.1a, 3.1b). For the specimens provided to free compression test (Fig. 3.1a), the dimension of radial direction (R-direction, h_0) was measured at the center point of specimens with a micrometer (OMV-25MX, Mitutoyo Corp., Kawasaki, Japan); the dimensions of longitudinal (L-direction) and tangential directions (T-direction) were measured at the centerline of each direction with a digital caliper (CD-15CP, Mitutoyo Corp., Kawasaki, Japan). The cross-sectional area was calculated using the image processing software ImageJ (Rasband 1997-2012; Schneider *et al.* 2012). In addition, the wood density before free compression test was also calculated using W_1, h_0 and the value of cross-section area (AD, WT, EB: air-dried density; OD: oven-dried density). For dynamic mechanical analysis (DMA) specimens (Fig. 3.1b), R-direction and T-direction dimensions were measured at the centerline of each with the above-noted digital caliper.

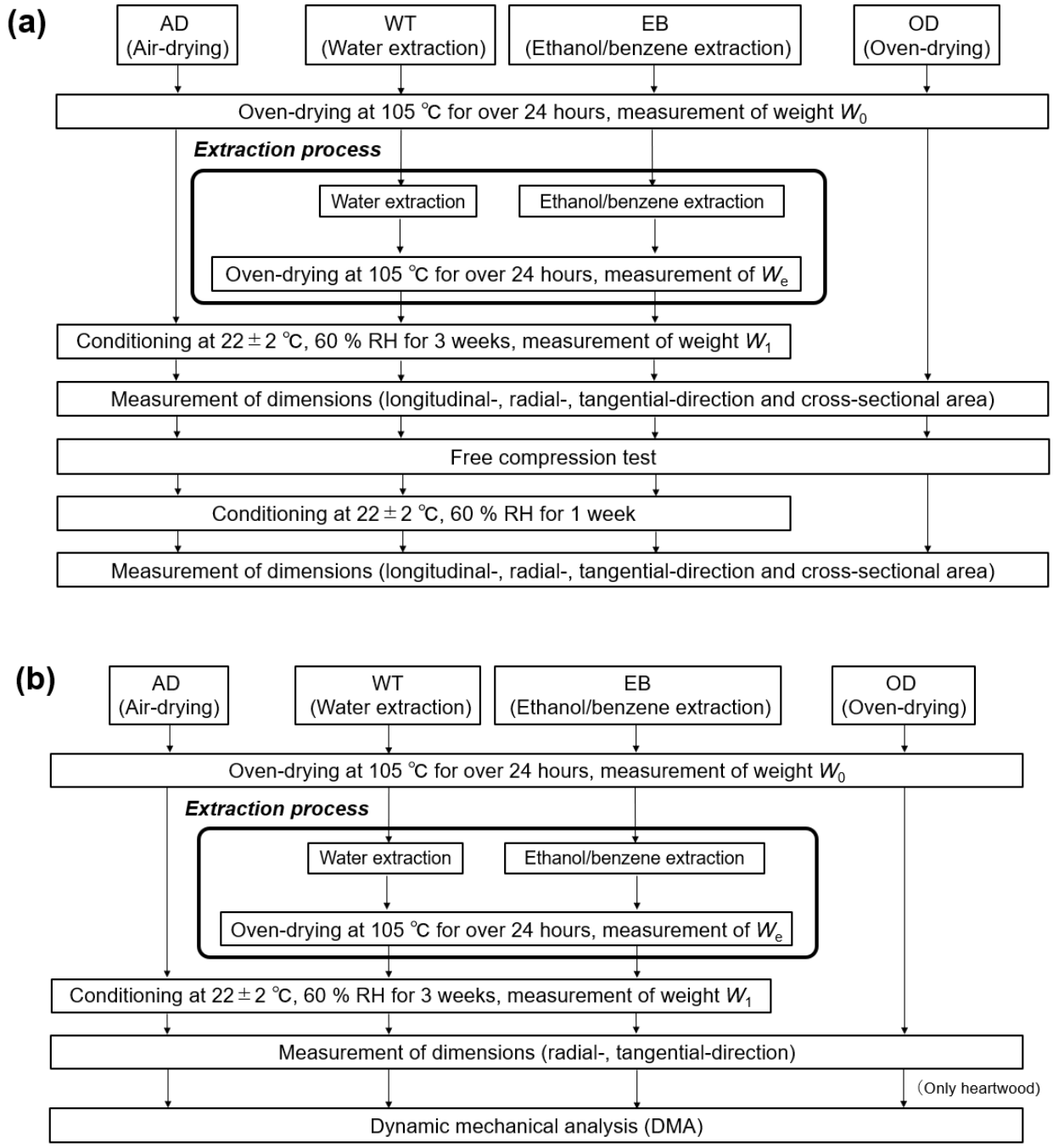


Fig. 3.1 Experimental procedures for: **(a)** free compression test, 5 replicates of disk-shaped specimen for AD, WT, EB and OD; and **(b)** for dynamic mechanical analysis (DMA), 5 replicates of rectangular specimen for AD, WT and EB.

3.2.3 Free compression test

The free compression test was performed with a universal testing machine (Instron 5582, Instron Co., MA, USA) as illustrated in Fig. 3.2. Specimens were placed on the lower punch controlled at 120 °C, and held in place with the upper punch without loading for the pre-heating time of 60 s. (Fig. 3.2). They were then compressed at a constant speed (0.02 mm/s), while both compressive stress (P) and gap displacement caused by deformation of specimens (h_s) were measured. Compression was also performed without specimens, and the P and the gap displacement caused by deformation of punches (h_b) were measured. The actual displacement (h) was calculated using Eq. 3.3.

$$h = h_s + h_b \tag{3.3}$$

The stress-strain curve was described using nominal strain (ε) and nominal stress (σ) calculated using equations 3.4 and 3.5:

$$\varepsilon = 1 - (h/h_0) \tag{3.4}$$

$$\sigma = P/(\pi d^2/4) \tag{3.5}$$

where h_0 is the initial specimen thickness (in the R-direction), π is the circular constant, and d is the diameter of the punch (d = 15 mm). Specimens were compressed to a maximum compressive load of 20 kN, equivalent to 113 MPa in compressive stress. In this test, water vapor pressure, caused by heating air-dried specimens, was neglected due to the small specimen size.

After the test, all specimens except for the OD were placed in a controlled chamber for 1 week at 22 ± 2 °C and 60 % RH for conditioning, and the parameters of specimen weight, dimensions (L-direction, R-direction, and T-direction) and cross-section area, were measured (Fig. 3.1a). The parameters of OD were measured immediately after the test. Dimensional changes (D_c) caused by the test (L-direction, T-direction and cross-sectional area) were calculated by equation 3.6:

$$D_c = \frac{D_a - D_b}{D_b} \times 100\ (\%) \qquad (3.6)$$

where D_b and D_a are the dimensional values of specimens before and after the test, respectively.

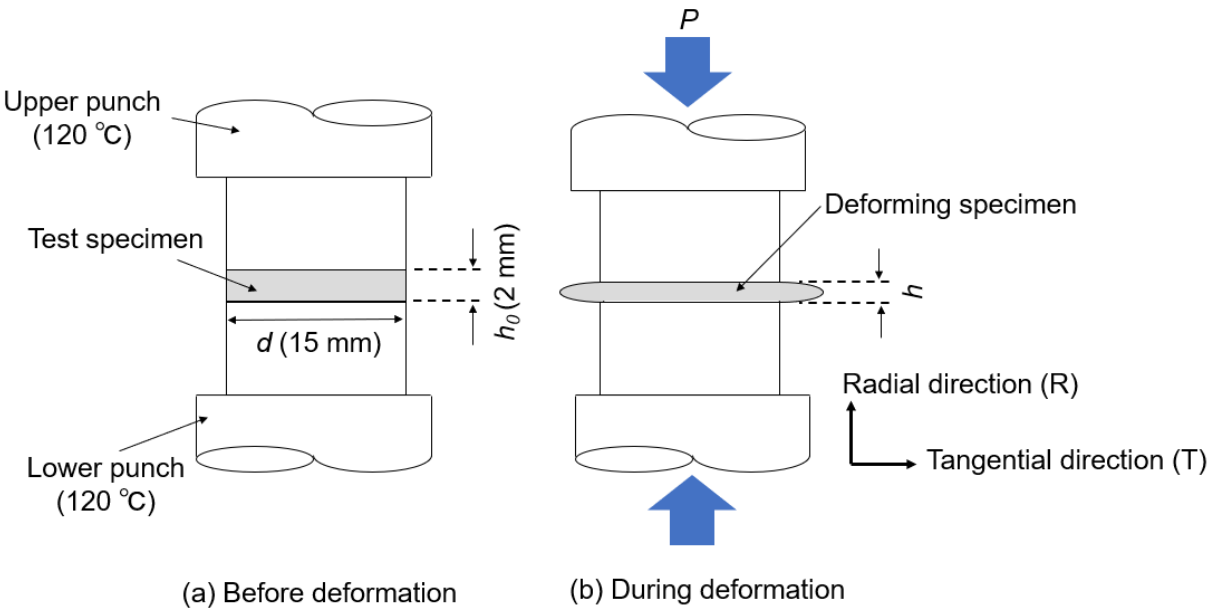


Fig. 3.2 Schematic diagram of free compression test. *d*: specimen diameter, h_0: initial thickness, *h*: deformed thickness.

The physical parameters, Young's modulus and maximum strain, were determined from the stress-strain curve collected through the test results. Young's modulus (E) was calculated from the angle of elastic deformation area in the curve. The stress at the flow-starting point (σ_f) was defined as the inflexion point of the stress-strain curve (Fig. 3.3), where the first peak of the derivative stress with respect to the strain ($d\sigma/d\varepsilon$). The strain at the inflection point was defined as the flow-starting strain (ε_f). The maximum strain (ε_m) was defined as the compressive strain value at the maximum compressive stress, σ_m = 113 MPa in the test.

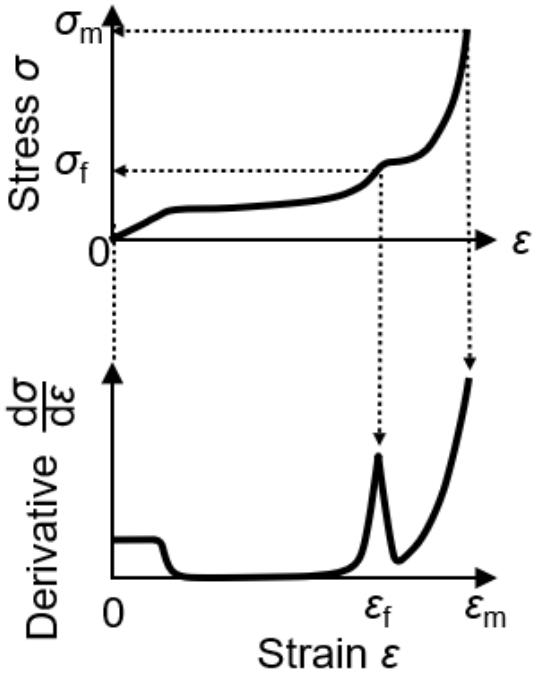


Fig. 3.3 Method for calculating the deformation parameters from the stress-strain curve.

3.2.4 Dynamic mechanical analysis (DMA)

The DMA was performed using a rheometer (ARES-G2, TA Instruments, New Castle, USA). The complex dynamic modulus (G^*) of viscoelastic materials generally represents the relation between the storage modulus (G') and loss modulus (G''), which are calculated from the dynamic performance with oscillation stress and strain by equations 3.7 and 3.8:

$$G^* = G'(\omega) + iG''(\omega) = \left|G^*\right| (\cos\delta + i\sin\delta) \qquad (3.7)$$

$$\tan\delta = G''(\omega)/G'(\omega) \qquad (3.8)$$

where i is the imaginary number, ω is the angular frequency, δ is the phase angle, and tanδ is the loss factor. In this analysis, G', G'' and tanδ were calculated from the amplitude and phase

difference (δ) of the oscillation curve for torque using the analysis software (TRIOS, TA Instruments, New Castle, USA).

The temperature-ramp test was conducted under a controlled environment by N_2 purge, from -50–250 °C at a constant temperature ramp rate (5 °C/min). Both edges of specimens were cramped at 20-mm in the L-direction, and loaded with dynamic torsion, 0.5% oscillation shearing strain at a constant frequency of 1.0 Hz (Fig. 3.4).

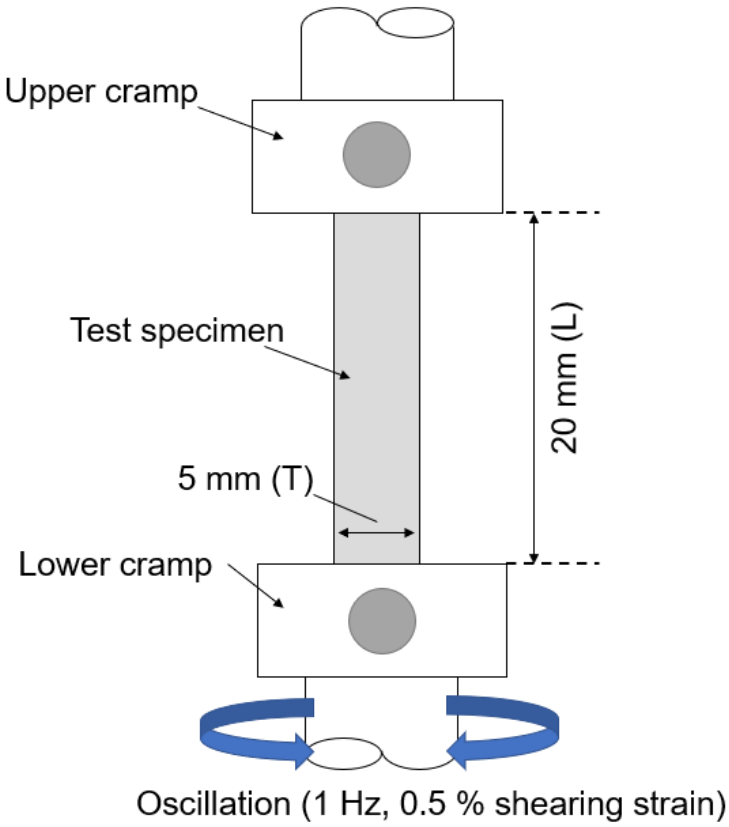


Fig. 3.4 Experimental set-up for the dynamic mechanical analysis using a rheometer.

3.2.5 Statistical analysis

The Tukey-Kramer test at 1% critical difference ($p < 0.01$) was used to analyze statistical differences between values (BellCurve for Excel, Social Survey Research Information Co. Ltd., Tokyo, Japan).

3.3 Results and discussion

3.3.1 Deformation characteristics

In the free compression test, both AD and WT specimens were flowed in the T-direction at 120 °C, while EB and OD specimens were not flowed (Fig. 3.5, 3.6). These findings suggest it was possible that flow deformation was promoted by the extractives and moisture.

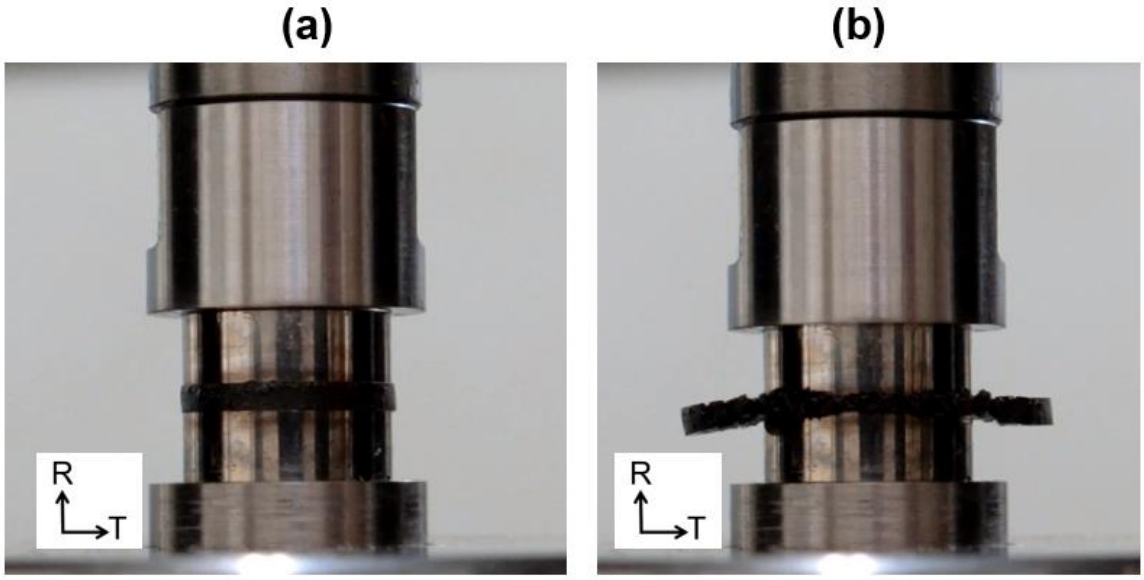


Fig. 3.5 Specimen in the free compression test: (**a**) before; and (**b**) after compression up to 113 MPa compressive stress.

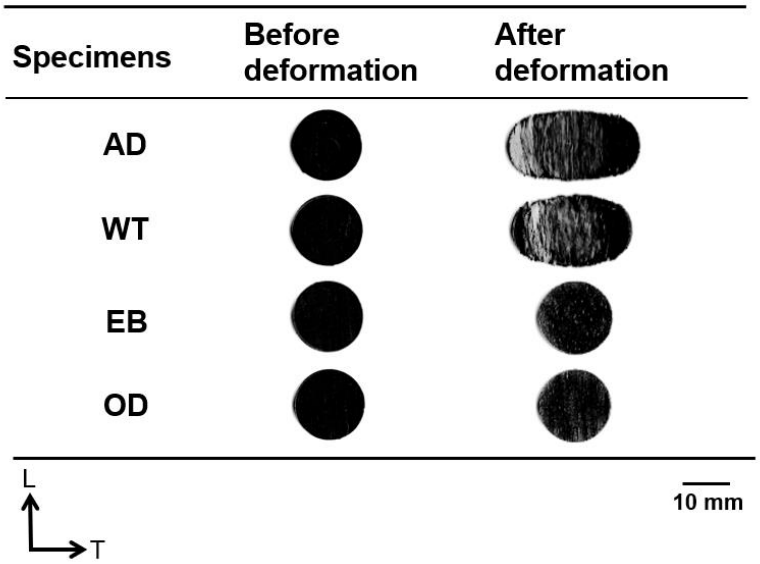


Fig. 3.6 Representative change in shapes of specimens before and after the free compression test.

In this compression test, AD showed the largest flow deformation compared to the other specimens. Table 3.1 lists the wood density, extraction rate, initial MC of the specimens and dimensional change for both the L- and T-directions together with specimens' cross-sections. In the cross-sectional area, AD was again the highest (average *ca.* 117 %) of all specimens with a significant difference at 1 % level (Table 3.1). For AD, the dimensional change in the T-direction was also the highest among specimens, whereas those in L-direction had no significant difference. These dimensional values in the vertical direction of compression loading show the displacement caused by flow deformation. The results suggest that the changes in the T-direction corresponded strongly to flow deformation based on the wood anisotropy: the lower strength on T-direction than L-direction. Yamashita *et al.* (2009) found that flow direction was mainly perpendicular to the fiber orientation, which was in keeping with the findings.

Table 3.1 Wood density, extraction rate, moisture content (MC) and dimensional changes due to free compression (mean ± SD).

Specimens	Wood density (g/cm^3)*	Extraction rate %*	Moisture content %*	Dimensional change %		
				Cross-section area*	L-direction*	T-direction*
AD	1.19 ± 0.01^b		8.24 ± 0.61^a	117.39 ± 7.90^c	-0.52 ± 1.21^a	97.45 ± 10.00^c
WT	1.16 ± 0.01^b	1.89 ± 0.44^a	8.88 ± 1.22^a	83.02 ± 3.38^b	3.54 ± 4.54^a	66.06 ± 24.24^b
EB	1.01 ± 0.03^a	16.12 ± 1.23^b	8.69 ± 0.11^a	1.01 ± 1.20^a	-0.51 ± 1.46^a	1.13 ± 0.63^a
OD	1.14 ± 0.01^b			1.15 ± 0.86^a	0.61 ± 0.55^a	2.29 ± 0.85^a

*: Means with the same letter are not significantly different (Tukey-Kramer test, $p < 0.01$) ($n = 5$).

Figures 3.7a and 3.7b show the σ_f and ε_f values for each specimen, the stress and strain values specialized at the flow-starting point. The σ_f value indicates the stress value necessary to generate flow deformation. AD showed the lowest value (average *ca.* 33.0 MPa) of all the specimens (Fig. 3.7a), while WT, EB and OD values were significantly higher. The ε_f value indicates the strain required to initiate flow deformation. There was a significant difference between the non-extracted specimens (AD and OD) and the extracted specimens (WT and EB) at 1 % level (Fig. 3.7b).

Figure 3.8 shows the maximum strain (ε_m) values. The ε_m value reflects the total displacement by the loaded compressive stress, *i.e.*, elastic deformation, densification deformation, and flow deformation. Here, there were significant differences among all specimens at 1 % level: *ca.* 73 % (AD), *ca.* 58 % (WT), *ca.* 28 % (EB) and *ca.* 10 % (OD) on average. The difference in the strain

between ε_m and ε_f ($\Delta\varepsilon = \varepsilon_m - \varepsilon_f$), which indicated the displacement due to flow deformation, showed a significantly high value in AD (*ca.* 58.4%) at 1 % level (Fig. 3.7b, 3.8). Although there was no statistical difference among the values of other specimens, the variation depended on extractives and moisture: *ca.* 21.2 % (WT), *ca.* 0.80 % (EB) and *ca.* 1.30 % (OD) (Fig. 3.7b, 3.8). Therefore, it was suggested that extractives and moisture amplified flow deformation.

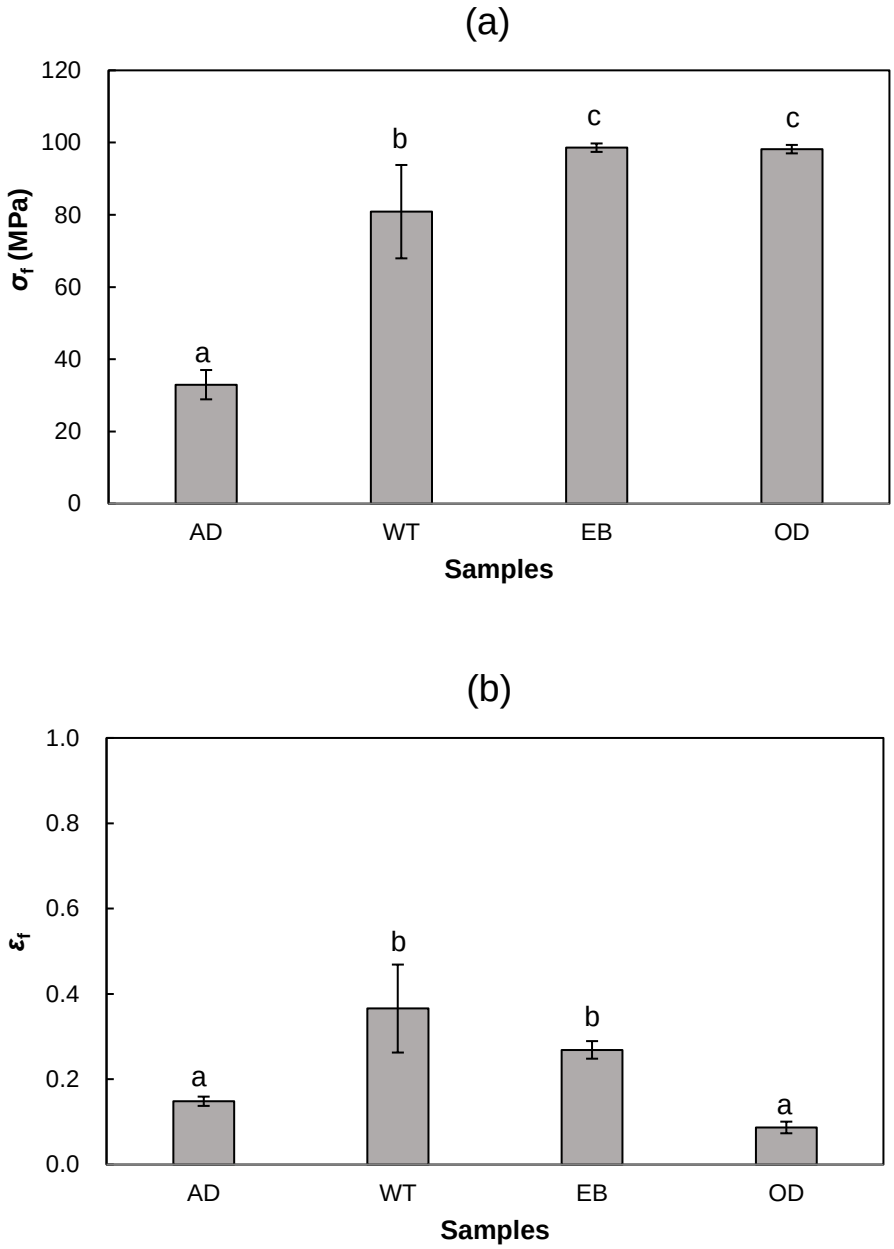


Fig. 3.7 Stress and strain at flow-starting point. (**a**) Compressive stress at the flow-starting point (σ_f). (**b**) Compressive strain at the flow-starting point (ε_f). Means with the same letter are not significantly different (Tukey-Kramer test, $p < 0.01$) ($n = 5$). Error bars represent standard deviations.

The ethanol/benzene extractives appeared to influence the deformation characteristics. Young's modulus (E) of specimens are shown in Fig. 3.9. The E values of WT and EB were statistically similar to that of AD at the 1 % level, despite their average values being more than 2 times higher: 300.9 MPa (AD), 641.5 MPa (WT) and 999.6 MPa (EB). The wood density of EB was lower than that of other specimens, whereas the MC of EB was also similar to those of AD and WT (Table 3.1). This suggested that the ethanol/benzene soluble extractives likely increased the elastic deformation of ABW. The σ_f value in EB was the highest among all specimens, although statistically equal to OD (Fig. 3.7a). The ε_f value in EB was higher than AD (Fig. 3.7b), although the ε_m value in EB was significantly lower than WT and AD with only 1 % of dimensional change (Table 3.1, Fig. 3.8). The value of $\Delta\varepsilon$ in EB was also significantly lower than AD (Fig. 3.7b, 3.8). These findings suggested that the ethanol/benzene soluble extractives helped promote the flow deformation of ABW.

The significant improvement of wood plastic deformation by increasing resin content has been reported previously (Shams *et al.* 2006; Seki *et al.* 2016a, 2016b, 2017). Wood extractives are generally distributed in cell walls and intercellular layers, as well as in lumen. Therefore, the presence of extractives potentially influences plastic deformation, despite their small amounts. In this experiment, EB showed a significantly higher extraction rate than that of WT: 16.12 % (EB) and 1.89 % (WT) on average (Table 3.1). The wood of EB was then significantly decreased due to extraction as previously noted. The ethanol/benzene soluble extractives comprising over 16 wt% of ABW heartwood (Table 3.1, Yin *et al.* 2018), apparently have a large impact on ABW deformation characteristics.

The water-soluble extractives might also influence deformation characteristics. Dimensional change in the cross-section of WT was significantly lower than that of AD: average *ca.* 83 % (Table 3.1). As shown in Table 3.1, both the wood density and the MC of WT was statistically equal to those of AD. However, the σ_f value in WT was higher than that of AD at 1 % level: average *ca.* 80.9 MPa (Fig. 3.7a). The value of $\Delta\varepsilon$ in WT was also significantly lower, as previously noted (Fig. 3.7b, 3.8). Furthermore, an increase of E in WT was observed though the value was not statistically different from that of AD (Fig. 3.9). Therefore, the presence of water-soluble extractives also contributed to promoting the flow deformation of ABW. These results might also indicate a positive relationship between water-soluble extractives and the deformation loading required to generate flow deformation.

The moisture in wood also affected the deformation characteristics. As shown in Table 3.1, flow deformation was not observed in OD, even though extractives were present with the similar wood density to AD. The σ_f value in OD was approximately three times higher than in AD (Fig. 3.7a), and $\Delta\varepsilon$ values were also lower than that of AD (Fig. 3.7b, 3.8). Furthermore, the *E* value of OD was markedly higher than those of the others (Fig. 3.9). This suggested that the deformation characteristics of ABW heartwood were affected by moisture. The moisture content significantly influenced the elastic deformation of ABW in the test, and possibly amplified even plastic deformation. Previous reports also noted that moisture contributed to wood-softening behavior, and that wood flow deformation could be improved in proportion to the increase in MC (Yamashita *et al.* 2009; Seki *et al.* 2016b). It is possible that the lower value of *E* contributed to densification deformation and flow deformation, while the change in *E* depended on the moisture content of specimens.

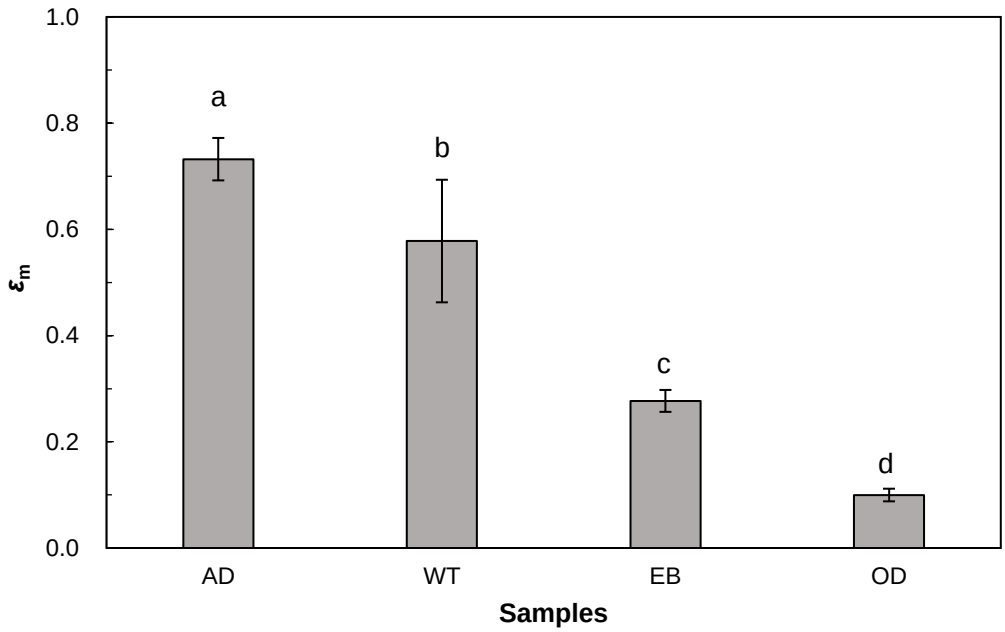


Fig. 3.8 Maximum strain at the maximum load (ε_m). Means with the same letter (a, b, c, d) are not significantly different (Tukey-Kramer test, $p < 0.01$) ($n = 5$). Error bars represent standard deviations.

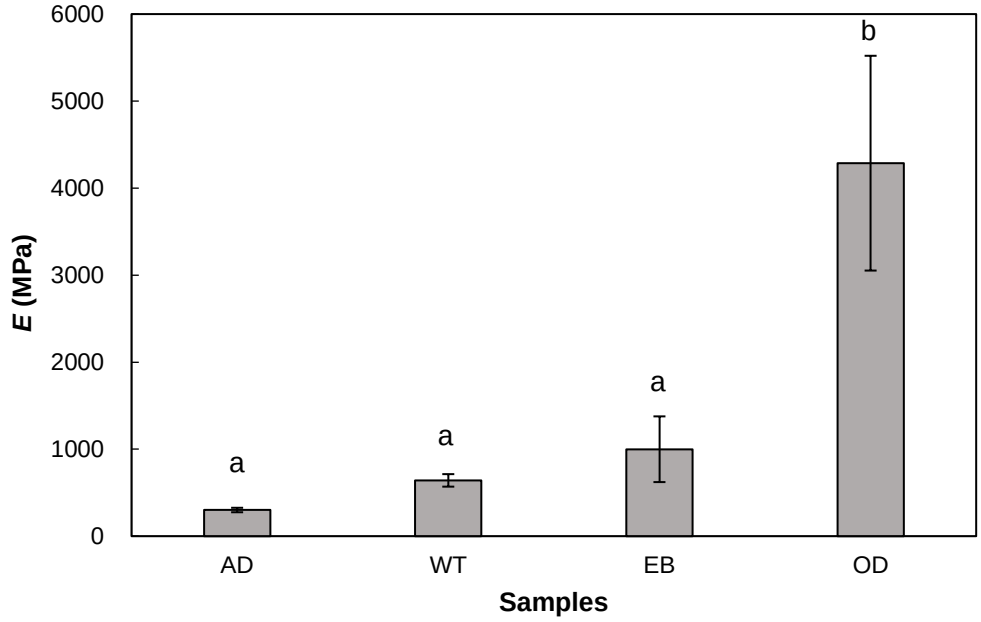


Fig. 3.9 Young's modulus (*E*) of specimens in the compressive fluidity tests. Means with the same letter (a, b) are not significantly different (Tukey-Kramer test, $p < 0.01$) ($n = 5$). Error bars represent standard deviations.

3.3.2 Temperature dependence of dynamic viscoelasticity

Table 3.2 presents the extraction rate and MC of specimens used for the DMA. The EB-heartwood had a significantly high extraction rate (average *ca.* 11.3 %) compared to the other specimens, including the EB-sapwood (average *ca.* 2.4 %). By contrast, the rates in the WT-heartwood and sapwoods were similar. Therefore, the ethanol/benzene soluble extractives were definitely concentrated in the heartwood. Meanwhile, the MCs of heartwoods (8–9 %) were a bit lower than those of sapwoods (9–11 %), and the extractions showed no effect. The MC of EB-sapwood was statistically equal to that of heartwood, which was significantly lower than those of the other sapwood specimens. Extractives have been suggested to affect the sorption properties of wood (Nzokou and Kamdem 2004; Hernández 2007; Hashemi and Latibari 2011), and the removal of extractives could result in an increase in swelling-shrinkage behavior (Mantanis *et al.* 1994, 1995; Adamopoulos and Voulgaridis 2012). Water-soluble extractives have been reported not to affect to wood sorption properties (Adamopoulos and Voulgaridis 2012; Jankowska *et al.* 2017). The results did not show any clear effects of the extractives on the sorption properties of ABW.

Table 3.2 Extraction rate and MC of specimens in the dynamic mechanical analysis (mean ± SD).

Specimen	Extraction Rate %*		Moisture Content %*	
	Heartwood	Sapwood	Heartwood	Sapwood
AD			8.01 ± 0.73[a]	10.83 ± 0.76[b]
WT	2.17 ± 0.78[a]	3.67 ± 1.34[a]	8.83 ± 0.84[a]	10.52 ± 0.59[b]
EB	11.32 ± 3.54[b]	2.36 ± 1.24[a]	8.72 ± 0.50[a]	9.13 ± 0.64[a]

*: Means with the same letter are not significantly different (Tukey-Kramer test, $p < 0.01$) ($n = 5$).

Figure 3.10 shows the temperature dependence of the dynamic viscoelastic parameters of AD, WT, EB and OD specimens. The curves of heartwood specimens (AD, WT and EB) were obviously shifted toward flattened curves in a range over 50 °C due to the extractions, whereas the curves of sapwoods were not shifted. In addition, the differences of the curves between AD and OD showed the effect of moisture on the parameters, the curves of OD indicated the thermal behavior of extractives. Amorphous polymers such as lignin and hemicellulose generally influence the temperature dependence of dynamic viscoelasticity in wood, with variable performance related to MC (Takamura 1968; Furuta *et al.* 2008, 2014). In this experiment, the modulus of transverse elasticity obtained by the DMA depended on the extractives and moisture, and were relevant to the flow deformation characteristics.

The G' values of all heartwood specimens overlapped over 200 °C (Fig. 3.10a). From -50 °C to 120–130 °C, AD, WT and EB heartwood specimens showed a similar pattern of curves, with a sharp decrease after 50–60 °C, they were overlapped over 120–130 °C. In addition, OD showed the similar pattern to other specimens with the highest value of all the specimens, however it overlapped over 200 °C. This trend coincided with the increase of Young's modulus in free compression test as described in Fig. 3.9. By contrast, all G' curves overlapped from -50–250 °C in the sapwood specimens. Different trends of G' curves were found between heartwood and sapwood in the range of 50 °C to 120–130 °C. Multiple inflection points could be clearly observed in both specimens of AD-heartwood and OD-heartwood, but the AD-sapwood specimens exhibited a single inflection point in this range.

The increase in G'' and tanδ generally indicate an increase in the viscosity of a material, which might be related to deformation characteristics. Since the large flow deformation in the AD-heartwood was noted, the results suggested that the patterns of G'' and tanδ curves are correlated with flow deformation in regard to the extractives and moisture, as discussed above (Figs. 3.6, 3.7, 3.8a, Table 3.1). The G'' curves showed that the AD-heartwood had multiple shoulder peaks, and

higher peak values in the range of 50–150 °C, suggesting that the viscosity of AD-heartwood was also increased, because the rapid increase of tanδ was simultaneously observed in this range (Fig. 3.10a). Although the similar patterns were observed in the curves of WT- and EB-heartwood, the values were decreased by the extraction. The G'' curve of EB-heartwood shifted almost overlapped that of sapwood specimens (Figs. 3.10a, 3.10b). The curves of sapwood specimens did not shift through the extractions with lower values in the range. As a result, sapwood might not show flow deformation like EB-heartwood in the free compression test. In addition, the potential of flow deformation under other temperatures was also assumed based on the curves of G'' and tanδ. The flow deformation of ABW heartwood was observed at 120 °C in this experiment (Figs. 3.5, 3.6). The results in Fig. 3.10a suggest that the AD-heartwood potentially flowed under temperatures lower than 120 °C due to the significant increase in G'' and tanδ in the range over 50 °C. Lower temperature should be useful not only for preserving the original mechanical properties but also for controlling viscosity in the mold.

Extractives were suggested to affect the softening temperature of the wood, which has particularly large amounts of ethanol/benzene extractives, like those reported in Pao rosa (*Swartzia fistuloides*) (Matsunaga and Minato 1998). The sharp increases of G'' and tanδ in the AD-heartwood at 50–80 °C might indicate the softening behavior of extractives. The curves G'' and tanδ in OD-heartwood suggested that the heartwood extractives showed the multiple peaks in the ranges of 50–100 °C and 150–210 °C, the values of G'' and tanδ in 100–150 °C were also affected by MC (Fig. 3.10a). Although all the tanδ curves of heartwoods were essentially overlapped in the range under 50 °C, the sharp increase of tanδ showed the significant increase of G'' in the range of 50–100 °C. This suggested the ethanol/benzene-soluble extractives were softened in the range over 50 °C. Furthermore, these parameters in the temperature ranges might be affected by amorphous polymers such as hemicellulose, which absorbed moisture. Since the E value of OD was significantly higher than that of AD in the free compression test (Fig. 3.9), the moisture potentially influenced physical properties of amorphous polymers in ABW heartwood. The curves of WT-heartwood also suggested that the water-soluble extractives affected the dynamic viscoelasticity of AD-heartwood (Fig. 3.10a). The water extraction resulted in *ca.* 30 % reduction in the G'' value of WT-heartwood at 120 °C, and the static parameters of WT-heartwood were statistically different from those of AD-heartwood (Figs. 3.7, 3.8). This trend was observed only in the heartwood specimens, even though the extraction rate in WT-sapwood was same as that of the WT-heartwood (Table 3.2). Although further studies are needed to identify the effect of water-soluble extractives,

it was assumed that some extractives were duplicated by the ethanol/benzene extraction due to the similarity of solubility parameters between ethanol and water (IUPAC, 2014).

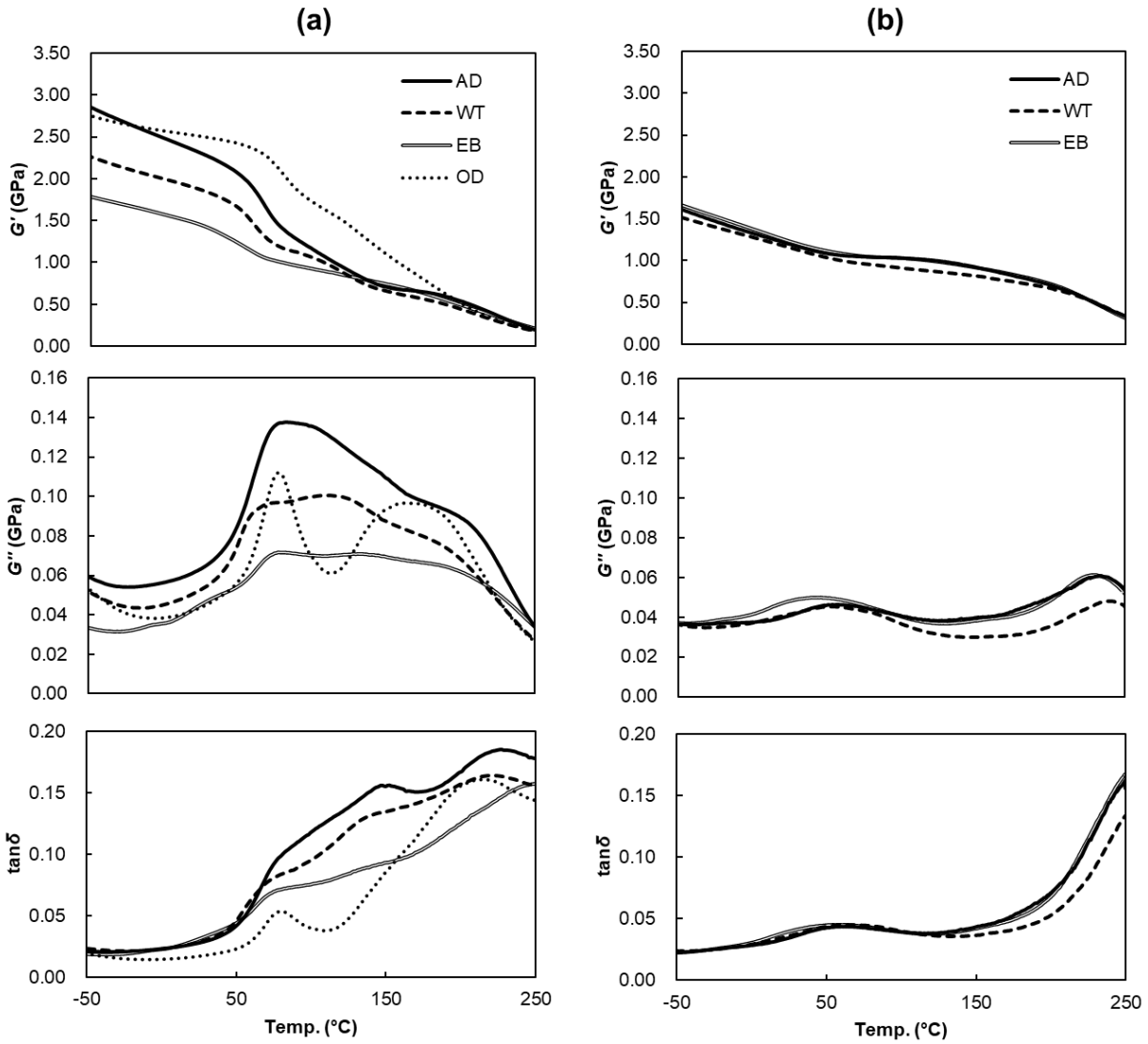


Fig. 3.10 Temperature dependence of the dynamic viscoelasticity among extraction treatments in (**a**) heartwood and (**b**) sapwood specimens.

3.5 Conclusions

The application of wood flow forming techniques in ABW could contribute to developing the effective utilization of wasted ABW timbers in the local forest sector. The present study demonstrated the deformation characteristics of air-dried ABW heartwood *via* the free compression test. The air-dried heartwood of ABW flowed at 120 °C, our findings suggested that the extractives in heartwood definitely resulted in flow deformation. The flow deformation depended mainly on

the ethanol/benzene-soluble extractives, which were highly concentrated in the heartwood. The ethanol/benzene-soluble extractives were suggested to be softened at temperatures over 50 ℃. The DMA results indicated that the increase in *G"* and tanδ were strongly related to flow deformation in the free compression test, thus the potential of flow formation at other temperatures was also assumed in the DMA. The flow deformation of ABW also depended on MC, although the oven-dried heartwood did not flow even with the presence of extractives. The MC affected mechanical properties, and an increase in MC might result in flow deformation. Consequently, our findings suggest the possibility that wood flow forming might contribute to further utilization of ABW timbers wasted in local sawmill factories.

3.6 References

- Adamopoulos S, Voulgaridis E (2012) Effect of hot-water extractives on water sorption and dimensional changes of black locust wood. *Wood Research* 57(1): 69-78.

- Donnelly BJ, Donnelly DMX, O'Sullivan AM, Predergast JP (1969) *Dalbergia* species VII, Isolation and structure of melanoxin a new dihydrobenzofuran from *Dalbergia melanoxylon* Guill. and Perr. (Leguminoseae). *Tetrahedron* 25(18): 4409-4414. DOI: 10.1016/S0040-4020(01)82981-1

- Eyton WB, Ollis WD, Sutherland IO (1967) The neoflavanoido group of natural products-I: Dalbergiones a new class of quinones. *Tetrahedron* 21(9): 2683-2696. DOI: 10.1016/S0040-4020(01)93924-9

- Furuta Y, Nakajima K, Nakatani T, Kojiro K, Nakamaru Y (2008) Effects of lignin on the thermal-softening properties of water-swollen wood. *Journal of the Society of Materials Science, Japan* 57: 344-349. (In Japanese)

- Furuta Y, Okuyama T, Kojiro K, Miyoshi Y, Kiryu T (2014) Temperature dependence of the dynamic viscoelasticity of bases of Japanese cypress branches and the trunk close to the branches saturated with water. *Journal of Wood Science* 60: 249-254. DOI: 10.1007/s10086-014-1402-6

- Hashemi H, Latibari J (2011) Evaluation and identification of walnut heartwood extractives for protection poplar wood. *BioResources* 6(1): 56-69.

- Hernández RE (2007) Swelling properties of hardwoods as affected by their extraneous substances, wood density, and interlocked grain. *Wood and Fiber Science* 39(1): 146-158.

- Jankowska A, Drożdżek M, Sarnowski P, Horodeński J (2017) Effect of extractives on the equilibrium moisture content and shrinkage of selected tropical wood species. *BioResources* 12(1) 597-607. DOI: 10.15376/biores.12.1.597-607

- Mantanis GI, Young RA, Rowell RM (1994) Swelling of wood. Part I: Swelling in water. *Wood Science and Technology* 28(2): 119-134. DOI: 10.1007/BF00192691

- Matsunaga M, Minato K (1998) Physical and mechanical properties required for violin bow materials II: comparison of the processing properties and durability between Pernambuco and substitutable wood species. *Journal of Wood Science* 44: 142-146.

- Miki T, Seki M, Sugimoto H, Shigematsu I, Kanayama K (2013) Preparation of three dimensional products using flow deformability of wood treated by small molecular resins. *Advanced Material Research* 856: 79-86. DOI: 10.4028/www.scientific.net/AMR.856.79

- Miki T, Sugimoto H, Shigematsu I, Kanayama K (2014) Superplastic deformation of solid wood by slipping cells at sub-micrometre intercellular layers. *International Journal of Nanotechnology* 11(5-8): 509-519. DOI: 10.1504/IJNT.2014.060572

- Nzokou P, Kamdem DP (2004) Influence of wood extractives on moisture sorption and wettability of red oak (*Quercus rubra*), black cherry (*Prunus serotina*), and red pine (*Pinus resinosa*). *Wood and Fiber Science* 36(4): 483-492.

- Rasband WS (1997-2012) ImageJ, U. S. National Institutes of Health, Bethesda, Maryland, USA, http://rsb.info.nih.gov/ij/, 1997-2012.

- Schneider CA, Rasband WS, Eliceiri KW (2012) NIH Image to ImageJ: 25 years of image analysis. *Nature Methods* 9: 671-675.

- Seki M, Tanaka S, Miki T, Shigematsu I, Kanayama K (2016a) Extrudability of solid wood by acetylation and in-situ polymerization of methyl methacrylate. *BioResources* 11(2): 4205-4036. DOI: 10.15376/biores.11.2.4025-4036

- Seki M, Kiryu T, Miki T, Tanaka S, Shigematsu I, Kanayama K (2016b) Extrusion of solid wood impregnated with phenol formaldehyde (PF) resin: Effect of resin content and moisture

content on extrudability and mechanical properties of extrudate. *BioResources* 11(3): 7697-7709. DOI: 10.15376/biores.11.3.7697-7709

- Seki M, Tanaka S, Miki T, Shigematsu I, Kanayama K (2017) Forward extrusion of bulk wood containing polymethylmethacrylate: Effect of polymer content and die angle on the flow characteristics. *Journal of Material Processing Technology* 239: 140-146. DOI: 10.1016/j.jmatprotec.2016.08.014

- Seshadri TR (1972) Plyphenols of *Pterocarpus* and *Dalbergia* woods. *Phytochemistry* 11(3): 881-898. DOI: 10.1016/S0031-9422(00)88430-7

- Shams MI, Yano H, Endou K. (2006) Compressive deformation of wood impregnated with low molecular weight phenol formaldehyde (PF) resin I: effects of pressing pressure and pressure holding. *Journal of Wood Science* 50: 337-342. DOI: 10.1007/s10086-003-0570-6

- Sugino H, Tanaka S, Kasamatsu Y, Okubayashi S, Seki M, Miki T, Umemura K, Kanayama K (2020) Influence of Electron-beam Irradiation on Plastic Flow Deformation of Wood **(in Japanese)**. *Journal of the Japan Wood Research Society* 66(2): 59-66.

- Takamura, N. (1968) Studies on hot pressing and drying process in the production of fiber board. III. Softening of Fiber Components in Hot Pressing of Fiber Mat. *Journal of Japan Wood Research Society* 14(2):75-79. (In Japanese)

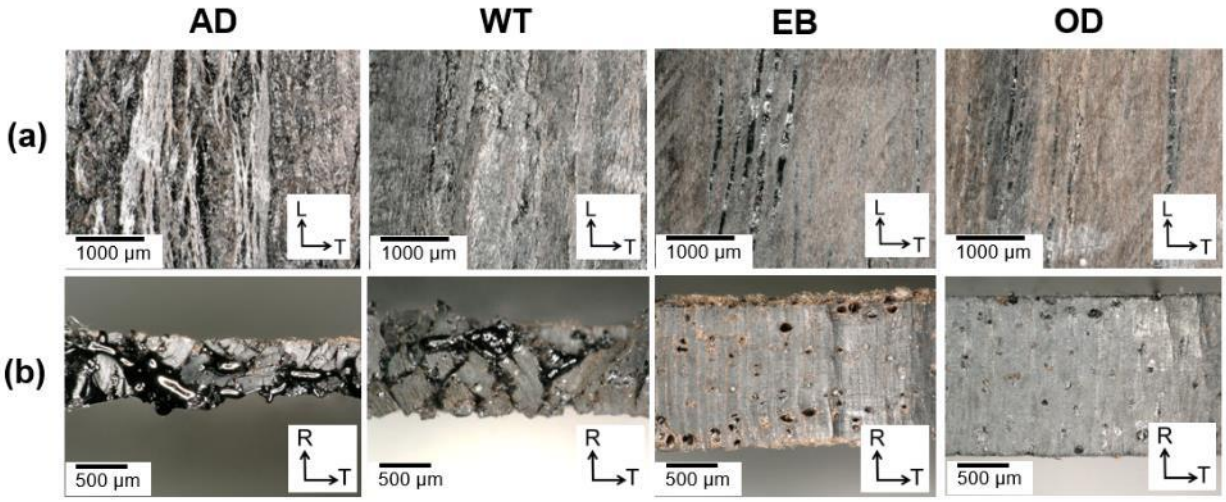
- Yamashita O, Yokochi H, Miki T, Kanayama K (2007) Producing Cups from Wood by Extrusion using Flow Phenomenon of Bulk Wood **(in Japanese)**. Nihon Kikaigakkai Ronbunshu 73(729): 2074-2078. DOI: 10.1299/kikaia.72.2074

- Yamashita O, Yokochi H, Miki T, Kanayama K (2009) The pliability of wood and its application to molding. *Journal of Materials Processing Technology* 209: 5239-5244. DOI: 10.1016/j.jmatprotec.2008.12.011

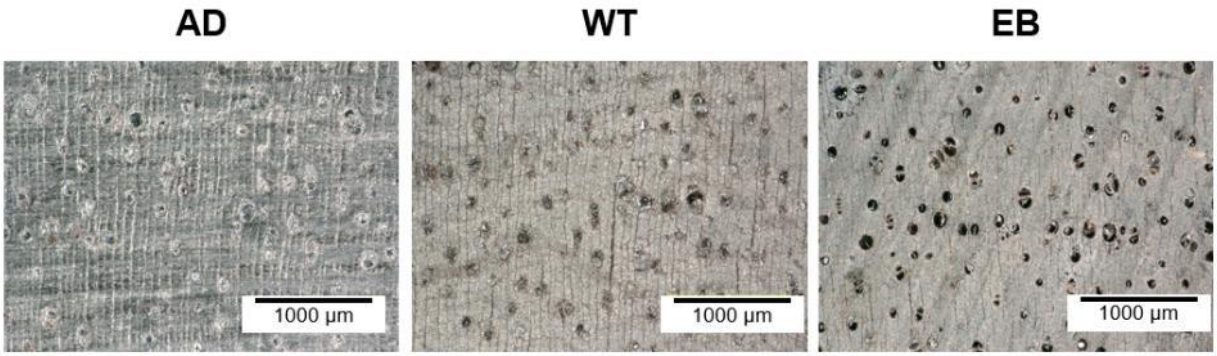
- Yin X, Huang A, Zhang S, Liu R, Ma F (2018) Identification of three *Dalbergia* species based on differences in extractive components. *Molecules* 23(9): 1-11. DOI: 10.3390/molecules23092163

3.7 Appendices

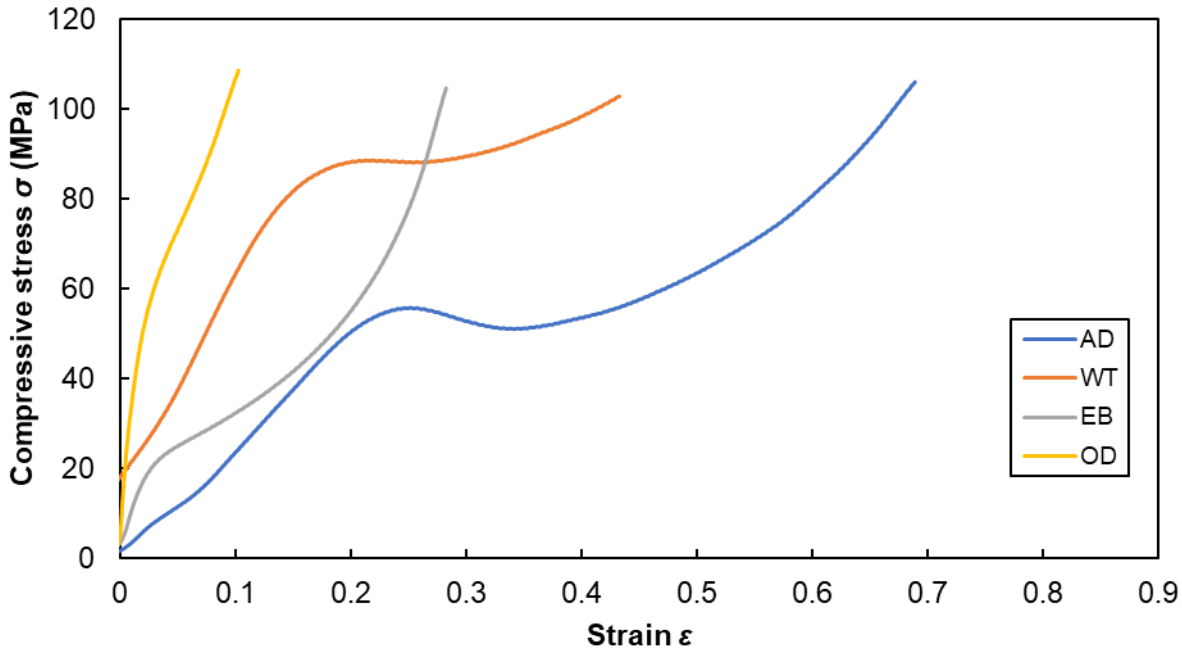
Appendix 3.1 Representative microscopic images of specimens after free compression test. **a:** Tangential section; **b:** Cross section.



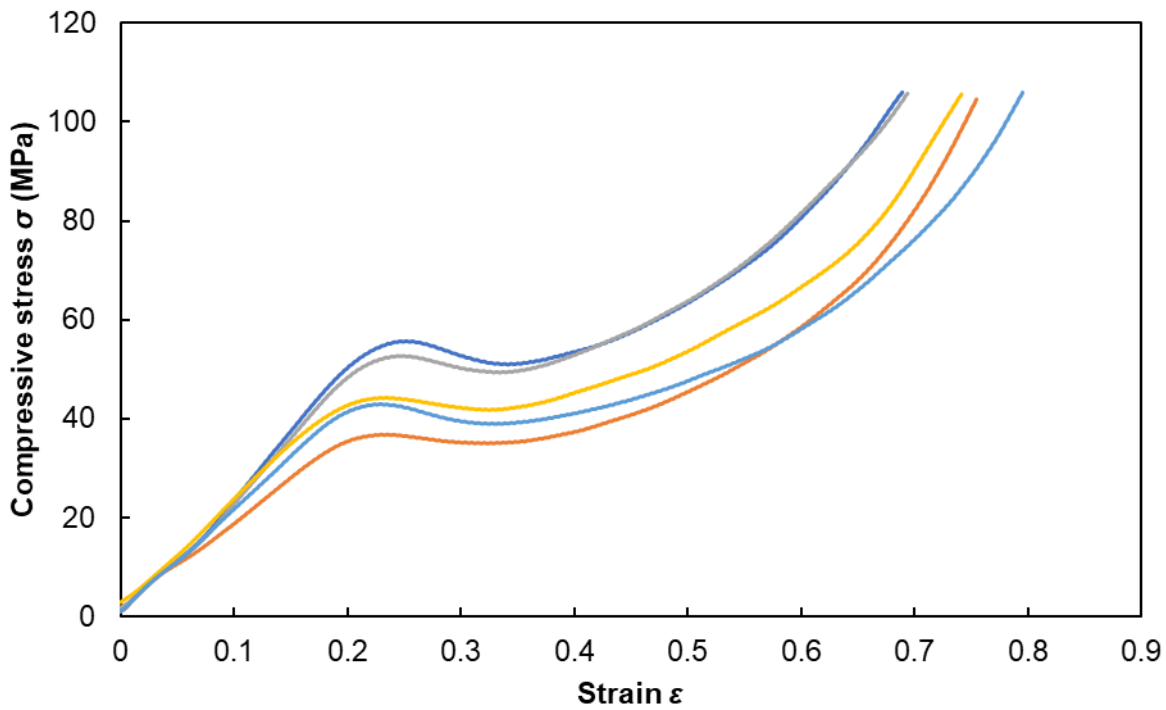
Appendix 3.2 Representative microscopic images of ABW heartwood specimens.



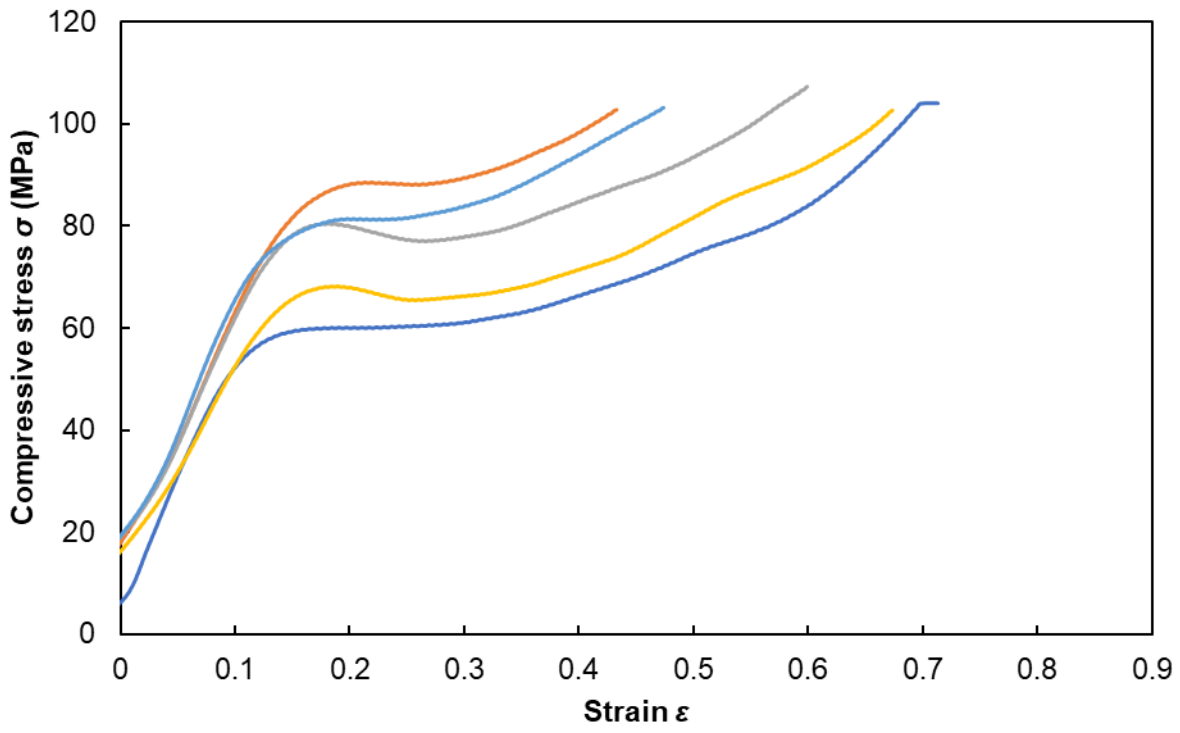
Appendix 3.3 Representative strain-stress curves in free compression test.



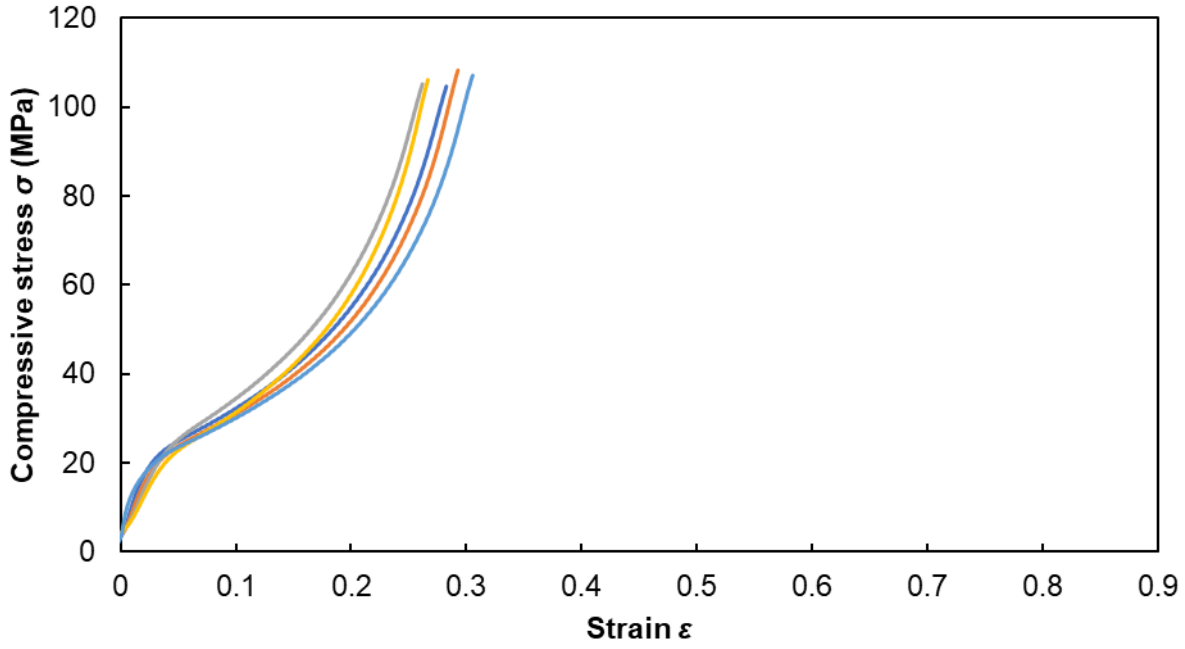
Appendix 3.4 Strain-stress curves of AD-specimens in free compression test (n = 5).



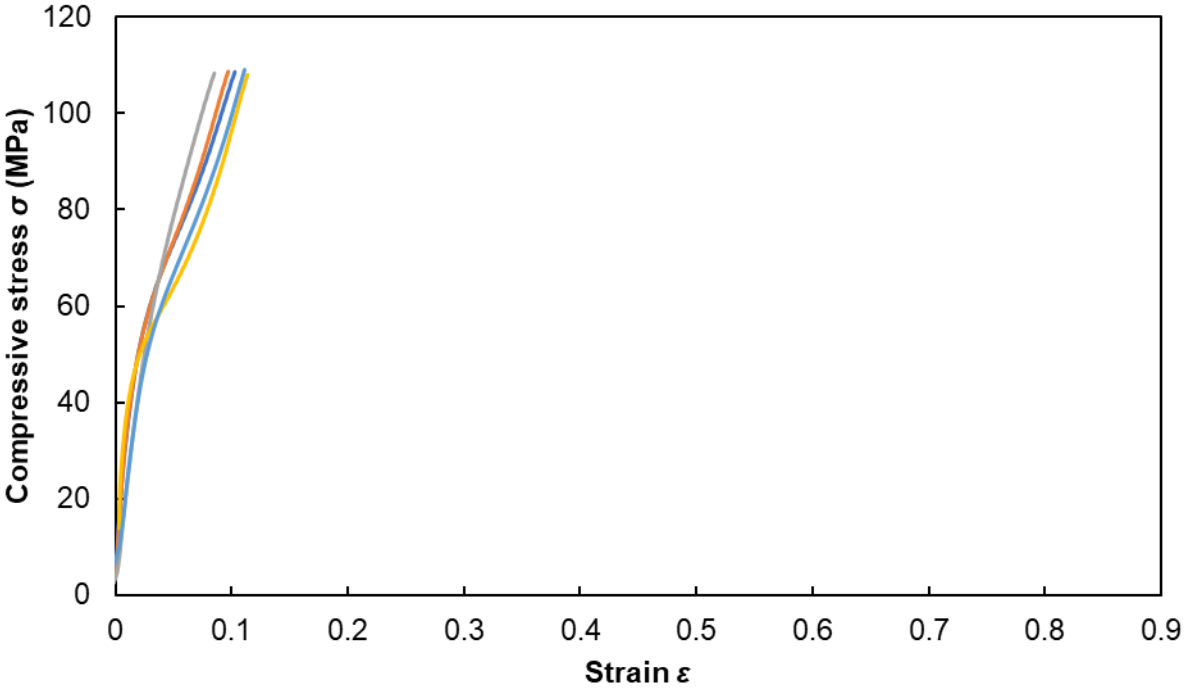
Appendix 3.5 Strain-stress curves of WT-specimens in free compression test (n = 5).



Appendix 3.6 Strain-stress curves of EB-specimens in free compression test (n = 5).



Appendix 3.7 Strain-stress curves of OD-specimens in free compression test (n = 5).



CHAPTER 4

CHALLENGES FOR PROMOTING SUSTAINABLE FOREST UTILIZATION: BIOLOGICAL PERFORMANCE OF LOCAL TREES

To achieve sustainable utilization of African Blackwood (ABW: *Dalbergia melanoxylon*), the suitable forest management is necessary for producing high-quality trees in local forests. Biological performance of timbers is a useful parameter to expand the potential utilization, especially in case of tropical species. In Chapter 4, the biological performance of ABW and other local Tanzanian species was studied to collect preliminary data for developing further uses for these local timbers. Five local species, including ABW, were exposed to both subterranean termites (*Coptotermes formosanus*) and two wood decay fungi (White rot fungus (*Trametes versicolor*) and Brown rot fungus (*Fomitopsis palustris*)) according to Japanese standard test methods. The heartwood of African Blackwood had high durability against both termite and fungal attacks, as well as the highest air-dried density of all test species. Some species also indicated a higher durability, even though they had a lower density than that of ABW heartwood. The results showed the importance of heartwood extractives in terms of biological performance for the local Tanzanian timbers. It was suggested that ABW heartwood was clearly useful as a high-durability material in addition to current major applications. The potential of the other local species was also suggested in terms of further timber utilization. These results presented fundamental information about sustainable forest management based on the effective utilization of local timbers.

4.1 Research objective

The main object in this chapter was to evaluate the natural resistance of Tanzanian local tree species to biological attacks (termites and wood decay fungi). The natural resistance of ABW might be a key aspect in terms of understanding the growth traits of high-quality timbers that are relevant to the extractives concentrated during the heartwood formation. However, there is little information about the biological performance of ABW and other co-existing species that exist in local forests.

Species having high biological performance are potentially useful for developing the further timber utilization, which can create the extra benefit through the local forestry. The ABW trees co-exist with other local species, *e.g.*, *Acacia nigrescens*, *Afzelia quanzensis*, *Pterocarpus angolensis*, *Millettia stuhlmannii*, and *Combretum* spp. (Nakai *et al.* 2019, Table 2.1, Fig. 2.4). Both *Af.*

quanzensis and *P. angolensis* grow throughout the deciduous broadleaf savannas and Miombo woodlands in eastern and southern Africa (Cunningham 2016). These wood species have also been regarded as an economically important species for local communities through industrial use as furniture or building materials. *Millettia stuhlmannii* and *Ac. nigrescens* are similarly useful as timber materials, both in terms of their color and grain patterns, as well as their wood properties.

To conserve a healthy forest, *i.e.*, not only the target species (ABW) but also the surrounding local trees, it must be managed and utilized effectively. Further effective utilization of the local trees is necessary for the sustainable development of local communities. Therefore, local Tanzanian species were selected for the comparative study, each biological performance was evaluated based on fundamental wood physical/chemical parameters. The results preliminary contribute not only to achieving sustainable forest conservation and management of ABW trees for musical instruments, but to also promote the local community forestry efforts through further utilization.

4.2Materials and methods

4.2.1 Wood specimens

Wood specimens were prepared from five Tanzanian local species: *Dalbergia melanoxylon* (ABW), both heartwood and sapwood; *Afzelia quanzensis* (AQ), heartwood; *Pterocarpus angolensis* (PA), heartwood; *Millettia stuhlmannii* (MS), heartwood; and *Xeroderris stuhlmannii* (XS), heartwood. These are common species in the miombo woodlands of the Kilwa District, Lindi Region, Tanzania. In addition, the sapwood of a Japanese local species, *Cryptomeria japonica* (CJ), was selected for usage as a control sample (as shown in Table 1) (Ohmura *et al.* 2011). Due to the original ratio of sapwood found in the ABW logs, the sapwood samples of ABW were prepared with 10 vol% to 15 vol% of heartwood. All specimens (5 specimens per each species for termite test; 9 specimens per each species for decay test) were cut from air-dried timber that was maintained for longer than 3 months at room temperature. The air-dried weight of each specimen was measured *via* an electronic scale (GH-252, A&D Company Ltd., Tokyo, Japan), and the dimensions were measured *via* a digital caliper (CD-15CP, Mitutoyo Corp, Kawasaki, Japan) in order to calculate the air-dried density before exposure to biological tests.

Table 4.1 List of the wood species selected for the comparison tests and their sampled sections (HW: heartwood; SW: sapwood).

Local name	Scientific name	Family	Sampled Section	Abbreviation
Mpingo	*Dalbergia melanoxylon*	Fabaceae	Heartwood	ABW-HW
			Sapwood	ABW-SW
Mkongo	*Afzelia quanzensis*	Fabaceae	Heartwood	AQ-HW
Mpangapanga	*Millettia stuhlmannii*	Fabaceae	Heartwood	MS-HW
Mninga jangwa	*Pterocarpus angolensis*	Fabaceae	Heartwood	PA-HW
Mlondondo	*Xeroderris stuhlmannii*	Fabaceae	Heartwood	XS-HW
Sugi*	*Cryptomeria japonica*	Cupressaceae	Sapwood	CJ-SW

* Not a local Tanzanian species but the control species as a reference.

4.2.2 Wood chemical analysis

Ash, extractives and holocellulose were determined according to the referenced procedures with minor modifications (Japan Wood Research Society 2000; Hamada *et al.* 2018). Each specimen (ABW-HW, ABW-SW, AQ-HW, MS-HW, PA-HW and XS-HW) was powdered *via* an electric grinder (Vita-Mix Blender, Osaka Chemical Co. Ltd., Osaka, Japan). 60-mesh pass wood powders were oven-dried at 105 °C for over 24 h prior to the analysis processes. 5 replicates were provided for each analysis.

4.2.2.1 Extractives content

Water extraction process was performed as follows. 10 g of dried wood powder (W_0) was soaked in 150 mL of distilled water using a sealed Erlenmeyer flask. The soaked powder is stirred for 10 min. in the water bath at 45 °C with ultrasonic treatment (Branson 5510JDTH, Yamato Scientific Co., Ltd., Tokyo, Japan), and then kept in the controlled chamber at 45 ± 5 °C for 48 h. Ethanol/benzene extraction was performed as follows. 10 g of dried wood powder was put into the cylindrical filter paper (86R Thimble Filter, Advantec Toyo Kaisha, Ltd., Tokyo, Japan), and extracted in Soxhlet extractor using the mixture solvent of ethanol (99.5 %) and benzene (1:2 v/v) at 85 ± 5 °C, for 6 h.

After the extraction, the extracted wood powder was oven-dried at 105 °C for over 24 h to measure the extracted weight (W_e) with the electric scale. The extraction rate was calculated by equation 4.1 using W_0 and W_e;

$$\text{Extraction rate} = \frac{W_0 - W_e}{W_0} \times 100\ (\%) \qquad (4.1)$$

4.2.2.2 Holocellulose content

2.0 g of ethanol/benzene soluble extractive-free wood powder (W_0) was put into a 300 mL flask. 150 mL of distilled water, 1.0 g of sodium chlorite and 0.2 mL of acetic acid were added into the flask. The mixture was heated in a water bath at 75± 5 °C after agitation for 1 min., the flask was lightly closed by a glass-board. The mixture was maintained at the heating temperature for 1 h, and 1.0 g of sodium chlorite and 0.2 mL of acetic acid were added and agitated again. This addition was repeated after each hour during 3 additional hours until when the wood sample became completely white. The mixture was cooled under 50 °C, the white residue of holocellulose was filtered on a glass filter (1GP16, Shibata Scientific Technology Ltd., Saitama, Japan) on a Büchner funnel, washed successively with distilled water and acetone. Then, the washed residue was dried at 105 °C to constant weight (W_H). The holocellulose content was calculated as follows:

$$\text{Holocellulose} = \frac{W_H}{W_0} \times 100\ (\%) \qquad (4.2)$$

4.2.3 Termite test

The termite test was conducted as a no-choice feeding test, according to JIS K 1571:2010 (2010), using the subterranean termite, *Coptotermes formosanus*. A wood sample measuring 20 mm (L) × 10 mm (R) × 10 mm (T), was placed on the plaster bottom of a cylindrical acrylic container (60 mm in height and 80 mm in external diameter) with a plastic mesh sheet (Fig. 4.1). A total of 150 mature *C. formosanus* workers and 15 *C. formosanus* soldiers were obtained from a laboratory colony maintained in the Deterioration Organisms Laboratory (DOL) at the Research Institute for Sustainable Humanosphere (RISH), Kyoto University, and introduced into the test container with 5 replicates for each species. The assembled containers were placed on a water-moistened cotton pad and kept at a temperature of 28 ± 2 °C and a relative humidity (RH) greater than 80 % for 3 weeks in the dark. The mass loss of each test specimen was calculated from the

difference of the oven-dried weights before and after the test at 60 ± 2 °C for 48 h. The termite mortality and consumption rates were also calculated after the test period. The wood consumption rate, *i.e.*, the total amount of the sample eaten by an individual worker per day, was determined from the mortality and mass loss, according to the assumption that the mortality of the workers developed linearly during the test period. The value was calculated based on the following equation:

$$\text{Wood Consumption Rate} = \frac{W_L/P/N_I}{(P \cdot N_I)/\int_0^P \left[\left(\frac{N_S - N_I}{P}\right)x + N_I\right]dx} \qquad (4.1)$$

where W_L is the mass loss of wood specimen, P is the test period, N_I is the number of introduced workers before the test period, and N_S is the number of survived workers. Furthermore, starvation controls were also prepared to discuss toxicity or/and repellency extractives.

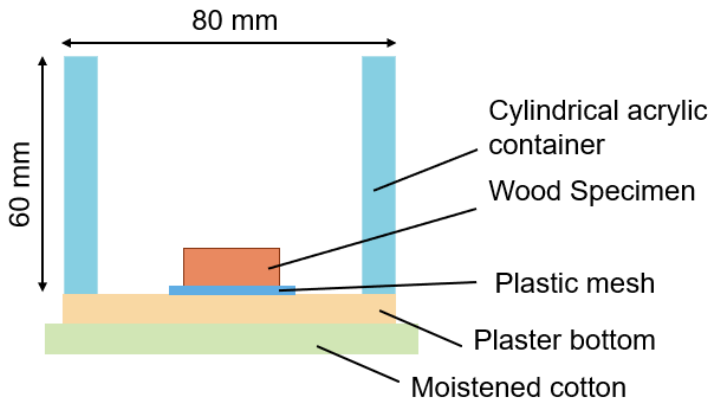


Fig. 4.1 Experimental set-up for no-choice termite feeding test.

4.2.4 Decay test

The decay test was conducted according to JIS K 1571:2010 (2010), with a specimen size of 10 mm (L) × 10 mm (R) × 20 mm (T). Three specimens were exposed to a monoculture of either *Trametes versicolor* (COV), a white rot fungus, with an accession number of FFPRI 1030, or *Fomitopsis palustris* (TYP), a brown rot fungus, with an accession number of FFPRI 0507 in a glass jar at a temperature of 26 ± 2 °C for 12 weeks in the dark (Fig. 4.2). The accession numbers were associated with the Forestry and Forest Products Research Institute, Tsukuba, Japan. Three decay jars were prepared with 9 replicates for each species. The percent mass loss of each specimen was calculated according to the same procedure described in the termite test.

Fig. 4.2 Wood Specimens after 12 weeks exposure of decay tests. **Left**: *Trametes versicolor* (COV), **Right**: *Fomitopsis palustris* (TYP).

4.2.5 Statistical analysis

The results from the biological tests were compared via the Tukey-Kramer test at 5 % critical difference (BellCurve for Excel, Social Survey Research Information Co. Ltd., Tokyo, Japan), in order to analyze the resistance of the samples to each biological attack.

4.3 Results and discussion

4.3.1 Air-dried density of the wood specimens

Table 4.2 shows the mean air-dried density of each specimen used in the present experiment. The densities of all the Tanzanian species were 2 to 3 times higher than the control specimen, CJ-SW. Of all species samples, ABW-HW had the highest density (*ca.* 1.3 g/cm^3), with a significant difference from ABW-SW at the 5 % level. There was no significant difference between ABW-SW and the other 3 species, AQ-HW (p = 0.1290), MS-HW (p = 0.9018), and PA-HW (p = 0.8705). Furthermore, there was no statistical difference among the other 3 species. In contrast, although the density of XS-HW was relatively lower than those of the other Tanzanian species, it was also statistically the same as AQ-HW, MS-HW, and PA-HW at 5 % level.

Table 4.2 Average air-dried density of each species before exposure to the biological tests (mean ± SD).

Species	Air-dried Density (g/cm^3)*
ABW-HW	1.30 ± 0.01[d]
ABW-SW	0.96 ± 0.05[c]
AQ-HW	0.80 ± 0.04[bc]
MS-HW	0.90 ± 0.04[bc]
PA-HW	0.90 ± 0.03[bc]
XS-HW	0.76 ± 0.03[b]
CJ-SW	0.35 ± 0.02[a]

* Means with the same letter are not significantly different ($p < 0.05$) following Tukey-Kramer test (n = 14).

4.3.2 Wood chemical parameters

Table 4.3 shows wood chemical parameters of each species. The water-soluble extractives in ABW-HW was lower than other local species including ABW-SW, however the value in ethanol/benzene soluble extractives indicated the highest of all species (*ca.* 25.6 %), which was much higher value than those of the other hardwood species (Hamada *et al.* 2018). By contrast, ABW-SW showed significant low value in ethanol/benzene soluble extractives (*ca.* 1.6 %). The value of holocellulose in ABW-SW was the highest of all species (*ca.* 71.5 %), whereas the value in ABW-HW was *ca.* 51 %, that was statistically similar to the other dark-colored heartwoods (AQ-HW, MS-HW and PA-HW) at 5 % level. It was suggested that the chemical component of ABW-HW was quite different from ABW-SW, ABW-SW contained much water-soluble extractives such as hemicellulose and monosaccharide.

AQ-HW indicated the highest value in water soluble extractives (*ca.* 23 %) of all the species, both MS-HW and PA-HW also indicated the higher value than that of ABW-HW (MS-HW: *ca.* 17.6 %; PA-HW: *ca.* 18.2 %). Although AQ-HW indicated the second highest value in ethanol/benzene soluble extractives of all the species, both values in MS-HW and PA-HW were comparatively lower than other heartwoods (MS-HW: *ca.* 3.4 %; PA-HW: *ca.* 8.3 %). In case of these species, the holocellulose contents were not significantly different from that of ABW-HW at 5 % level. Therefore, the extractives of these species (AQ-HW, MS-HW and PA-HW) were mainly

comprised of water-soluble chemicals, moreover the higher density of ABW-HW might depend on the higher content of ethanol/benzene soluble extractives (Table 4.2, Table 4.3).

The chemical component of XS-HW was different from other heartwood species, and it indicated the similar trend to ABW-SW. XS-HW contained *ca.* 13.4 % of water-soluble extractives, however the content of ethanol/benzene extractives was only *ca.* 0.6 %, which was the lowest value of all the species including ABW-SW (Table 4.3). In addition, the content of holocellulose in this species was comparatively higher than those of the other heartwoods (*ca.* 63.8 %). Therefore, the chemical properties of XS-HW was similar to ABW-SW, and there might be no difference from the sapwood part in terms of chemical properties as well as biological performances.

Table 4.3 Wood chemical parameters of each species (mean ± SD).

Species	Water-soluble extractives %*	Ethanol/Benzene-soluble extractives %*	Holocellulose %*
ABW-HW	13.33 ± 0.72[a]	25.56 ± 3.73[d]	50.98 ± 6.16[a]
ABW-SW	16.74 ± 0.21[a]	1.57 ± 0.40[a]	71.53 ± 3.26[b]
AQ-HW	23.40 ± 2.78[c]	15.33 ± 1.69[c]	51.41 ± 1.16[a]
MS-HW	17.59 ± 1.82[b]	3.42 ± 1.03[a]	58.68 ± 6.17[a]
PA-HW	18.24 ± 1.48[b]	8.25 ± 0.54[b]	57.63 ± 0.77[a]
XS-HW	13.42 ± 0.54[a]	0.64 ± 0.12[a]	63.84 ± 2.41[b]

* Means with the same letter are not significantly different ($p < 0.05$) following Tukey-Kramer test (n = 5).

4.3.3 Termite resistance

The mortality rates of both the worker and soldier termites after the 3-week forced-feeding tests are shown in Fig. 4.3. The mean mortality rates for sample CJ-SW (the control) were 23.5 % for the workers and 46.7 % for the soldiers. The starvation control had a 38.3 % mean mortality rate for the workers and a 100 % mortality rate for the soldiers. The mean mortality rate of the workers for sample ABW-HW was 27.1 %, which was comparable to sample CJ-SW, but was significantly lower than that of the starvation control. For sample ABW-SW, the 22.9 % mean mortality rate of the workers was not significantly different from sample ABW-HW, but the mortality rate of the soldiers was significantly lower than sample ABW-HW (97.8 % in ABW-HW

and 80.0 % in ABW-SW). They were also significantly different from sample CJ-SW ($p < 0.05$). Three heartwood specimens (AQ-HW, MS-HW, and PA-HW) showed similar mortality rates to the starvation control without significant difference. The mortality rates of heartwood specimen, XS-HW, were statistically equivalent to sample CJ-SW (23.3 % for the workers and 38.7 % for the soldiers).

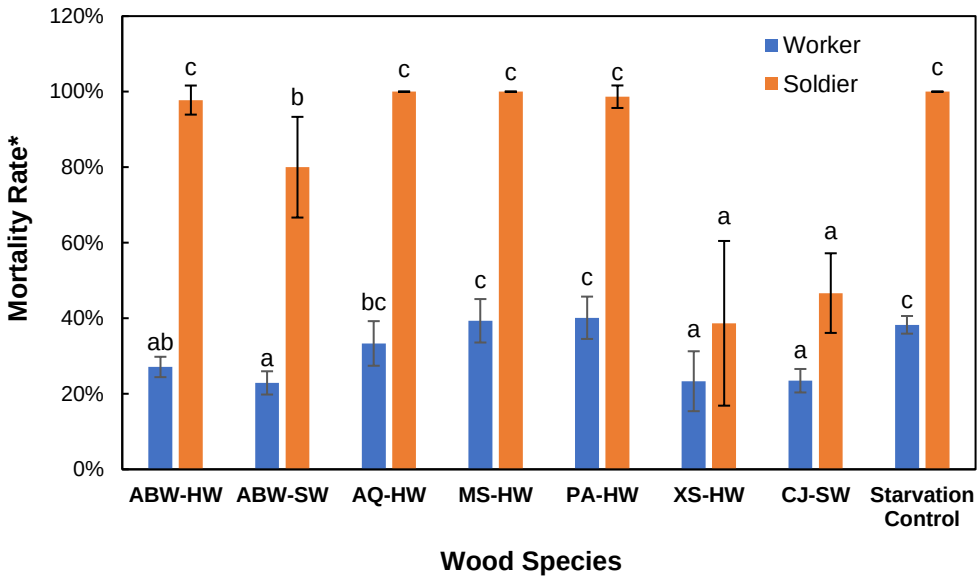


Fig. 4.3 The mortality rates of the workers and soldiers after the 3-week forced-feeding test with *Coptotermes formosanus* (mean ± SD) (n = 5). *Means with the same letter are not significantly different ($p < 0.05$) following Tukey-Kramer test.

Table 4.3 showed both the mass losses and the wood consumption rates in the termite tests. Sample ABW-HW had a mean mass loss value of 29.7 mg, which was significantly different from sample ABW-SW (119.2 mg). This value was statistically similar to the values for samples AQ-HW, MS-HW, and PA-HW ($p < 0.05$), although sample MS-HW had the lowest mean value among all species (19.6 mg). In contrast, there was no statistical difference between sample ABW-SW and sample XS-HW. Regarding the wood consumption rate of each species, a worker consumed 10.7 μg/day of sample ABW-HW, which was similar to the rates of samples AQ-HW, MS-HW, and PA-HW. All of the data for sample CJ-SW were significantly different from all the other species at the 5 % level.

Table 4.4 Mass Loss and Consumption Rate during the Termite Test (mean ± SD).

Species	Mass Loss (mg)*	Consumption Rate (µg/termite/day)*
ABW-HW	29.67 ± 5.20[a]	10.72 ± 2.02[a]
ABW-SW	119.17 ± 17.78[b]	42.73 ± 6.82[b]
AQ-HW	48.80 ± 7.92[a]	18.57 ± 2.70[a]
MS-HW	19.60 ± 4.34[a]	7.73 ± 1.54[a]
PA-HW	29.20 ± 5.40[a]	11.56 ± 1.83[a]
XS-HW	128.40 ± 49.39[b]	45.64 ± 15.86[b]
CJ-SW	177.80 ± 43.24[c]	63.82 ± 15.07[c]

* Means with the same letter are not significantly different ($p < 0.05$) following Tukey-Kramer test (n = 5).

The mortality rate of the workers for sample ABW-HW was significantly lower than the rates of samples MS-HW, PA-HW, and the starvation control (as shown in Fig. 4.3). However, the consumption rate of sample ABW-HW was statistically equivalent to the rates of samples MS-HW and PA-HW (as shown in Table 4.4). It has been suggested that the resistance of wood to termite attacks can be attributed to the density of the wood specimens, which is generally related to wood hardness (Acanakwo *et al.* 2019). It was confirmed in this experiment that the low-density species (samples ABW-SW and XS-HW) yielded a higher total mass loss over the high-density species (samples ABW-HW, AQ-HW, MS-HW, and PA-HW) when subjected to termite attacks (as shown in Table 4.2 and Table 4.4). Although the air-dried density of sample ABW-SW was approximately 0.96 g/cm^3 (as shown in Table 4.2), due to the heartwood portion mentioned above, the density of ABW-SW had been previously been reported by Malimbwi *et al.* (2000) as *ca.* 0.75 g/cm^3, which was comparable to the XS-HW specimens. The heartwood of *Xeroderris stuhlmannii* is susceptible to insect attack, especially from powder-post beetles (Lemmens 2007). Since worker termites primarily attacked the sapwood portion of the ABW-SW sample in the test, both the mass loss and the consumption rate for the ABW-SW sample was not different from the low-density wood species, which included the CJ-SW sample, despite its higher density (Table 4.4).

The density of sample ABW-HW (1.30 g/cm^3) was much higher than those of the other species samples (Table 4.2); however, the mortality rate of the workers was significantly lower than the mortality rate in samples MS-HW, PA-HW, and the starvation control (Fig. 4.3). The value was also statistically equivalent to samples ABW-SW, XS-HW, and CJ-SW, but the mortality rate of

the soldiers was significantly higher (Fig. 4.3). Workers generally provide nutrition to the soldiers; thus, the difference in soldier mortality rates could indicate a difference in the feeding activities of the workers. Since the mortality rates of the workers and the soldiers in samples MS-HW, PA-HW, and AQ-HW were similar to the mortality rates of the starvation control (Fig. 4.3), it was likely that termite feeding activities against these species was low. The feeding mass of sample ABW-HW did not differ from the feeding mass in the other wood species (Table 4.4). These results suggested that other factors, *e.g.*, the wood extractives, played a role in the biological performance of the tested wood samples.

The biological activity of various wood extractives had been previously reported (Ohmura *et al.* 2000; Mburu *et al.* 2007; Borges *et al.* 2008; Tascioglu *et al.* 2013). In particular, the high anti-feedant effects of some flavonoids, which included taxifolin and quercetin, against *C. formosanus* had been demonstrated (Ohmura *et al.* 2000). Other flavonoids, *e.g.*, polyphenols, isoflavonoids, and neoflavonoids, had also been obtained from Fabaceae trees, which included the *Dalbergia* and *Pterocarpus* species (Seshadri 1972; Sekine *et al.* 2009; Yin *et al.* 2018), and their resistance against termites and fungi had been determined with laboratory tests (Sekine *et al.* 2009). Considering these facts, the higher mortality rates of the MS-HW and PA-HW samples could be dependent on the presence of these extractives. In addition, according to the results of wood chemical analysis, both MS-HW and PA-HW indicated the lower content of ethanol/benzene soluble extractives than ABW-HW, whereas the water-soluble extractives were obtained in larger amount than ABW-HW as previously noted (Table 4.3). Some flavonoids studied previously belongs to the ethanol/benzene-soluble extractives. Therefore, the anti-feedant effects of ABW-HW might depend on the limited compounds which were similarly contained in MS-HW and PA-HW. Furthermore, some compounds of water-soluble extractives potentially affect the termite feeding activity.

4.3.4 Decay resistance

Figure 4.4 showed the percent mass losses of the wood species after exposure to COV and TYP for 12 weeks. The mass loss values of sample ABW-HW, after exposure to both fungi, were the lowest among all tested species, and the mass loss values of samples MS-HW and PA-HW were also lower compared to those of the other tested species. The mass loss caused by COV in sample ABW-SW was significantly higher than the mass loss in samples ABW-HW and MS-HW, but it was not significantly different from samples AQ-HW and PA-HW. In the case of TYP, the mass

loss values of samples ABW-HW and MS-HW were the lowest among all the tested species, although they were not statistically different from samples ABW-SW, AQ-HW, and PA-HW. In contrast, the mean mass loss values of sample XS-HW were significantly higher than those of other tested Tanzanian species (20.8 % in COV and 34.4 % in TYP on average) but were similar to the mean mass loss values of sample CJ-SW in TYP at a 5 % level.

According to the results of the decay tests, the decay resistance of the tested wood specimens was concluded to be similarly attributed to both wood properties, *i.e.*, the density and the chemical component in particular the extractives content. It was reported that higher density wood species typically decayed more slowly than lower density species (Chambers *et al.* 2000). It had been suggested that the influence of the heartwood extractives on the durability of the wood went beyond their fungicidal properties. The possible functions of the extractives against fungal colonization included an antioxidant effect (Schultz and Nicholas 2000). Some extractives found in samples ABW-HW, MS-HW, and PA-HW could strongly affect their durability against decay fungi. By contrast, the decay resistance of XS-HW was significantly inferior to other species. The mass loss was also much higher than the other sapwood, ABW-SW (Fig. 4.4). As previously noted, the chemical component of XS-HW was clearly different from other heartwood species, and it was similar to that of ABW-SW (Table 4.3). Therefore, the low resistance of XS-HW might result in some different compounds from ABW-SW.

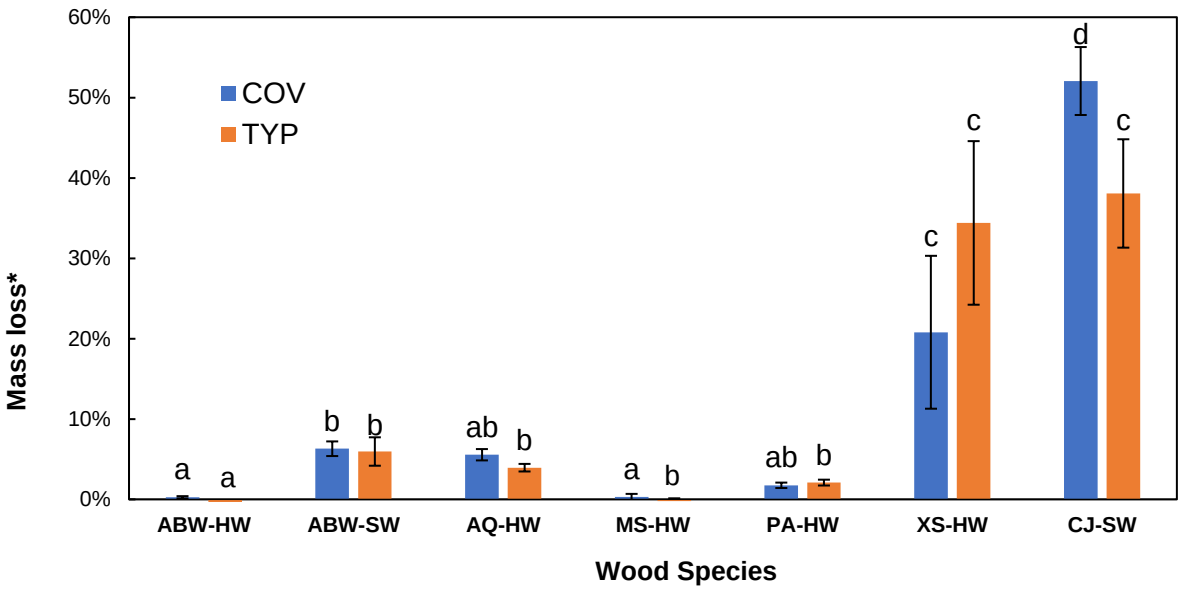


Fig. 4.4 Mass loss percentages of the tested wood specimens after 12-week exposure to COV and TYP (mean ± SD) (n = 9). * Means with the same letter are not significantly different ($p < 0.05$) following Tukey-Kramer test.

4.3.5 Biological performance of the test species

Consequently, high biological performance in the heartwood of African blackwood (*Dalbergia melanoxylon*) was found in this experiment, while the sapwood was significantly less resistant to termite and fungal attacks. The performance of ABW-HW was relatively superior to the other Tanzanian wood species, which could be strongly related to the high concentration of extractives found in the wood. Since the volume percentage of heartwood in the ABW logs had been estimated at over 80 %, the durability of the heartwood made a large contribution to the natural biological resistance of this species (Malimbwi *et al.* 2000).

The extractives found in ABW-HW were reported to be different from those of other *Dalbergia* species, as well as at higher concentrations, which would contribute to the advantages of ABW as a material (Yin *et al.* 2018). The flavonoids including neoflavonoids, *e.g.*, melanoxin, have been previously isolated from the extractives of ABW heartwood (Donnelly *et al.* 1969; Donnelly and O'reilly 1975), and Amri and Juma (2016) confirmed the antimicrobial potential of the extractives from the stem bark of ABW with the presence of flavonoids. In addition, the heartwood of both *Pterocarpus angolensis* (PA) and *Millettia stuhlmannii* (MS) showed a higher level of termite resistance than ABW-HW displayed. These woods are widely utilized for construction or furniture in African countries, *e.g.*, Tanzania and Mozambique. *Afzelia quanzensis* (AQ) is also commercially harvested and utilized in these countries (Cunningham 2016). It was suggested that such local timbers could be further utilized and applied to a broad range of global demands, particularly MS and PA, as materials for situations requiring high durability, *e.g.*, for exterior products.

The construction of a sustainable forestry system based on the local community is a key concept for the future of forestry. Useful trees, such as ABW, are now becoming the main sources of profit in local forestry, in addition to the current charcoal and fuel-wood production (Miya *et al.* 2012). Therefore, the cultivation of high-quality trees that can meet the present market demand is necessary to achieve a sustainable forest. To cultivate such valuable trees, co-existing trees should be systematically harvested together with the target trees under a sustainable forestry system. Furthermore, the timbers also should be utilized efficiently to improve the timber yield. In the present findings, the potential of Tanzanian local species, including the ABW tree as well as other co-existing trees, was shown to support the local community *via* sustainable forestry.

4.4. Conclusions

The heartwood of African Blackwood (*Dalbergia melanoxylon*) was shown to have strong biological performance, whereas the sapwood was remarkably less resistant to termite and fungal attack. The results suggested that ABW-HW was clearly useful as a high-durability material such as an exterior material, in addition to its current major applications. Wood density was strongly related to the biological performance. The high-density species showed a higher durability than the low-density species. Furthermore, the contribution of heartwood extractives to the durability of the test species was also suggested through the biological tests.

The high resistance in other local species was found in the biological tests. The heartwood of *Millettia sthulmannii* and *Pterocarpus angolensis* especially showed a higher biological performance than that of the heartwood of *D. melanoxylon*. The high biological performance of other Tanzanian species could be useful for developing the further timber utilization in the local community forestry.

4.5. References

- Acanakwo EF, Sheil D, Moe SR (2019) Wood decomposition is more rapid on than off termite mounds in an African savanna. *Ecosphere* 10(1): 1-11. DOI: 10.1002/ecs2.2554

- Amri E, Juma S (2016) Evaluation of antimicrobial activity and qualitative phytochemical screening of solvent extracts of *Dalbergia melanoxylon* (Guill. & Perr.). *International Journal of Current Microbiology and Applied Sciences* 5(7): 412-423. DOI: 10.20546/ijcmas.2016.507.045

- Borges LMS, Cragg SM, Bergot J, Williams JR, Shayler B, Sawyer GS (2008) Laboratory screening of tropical hardwoods for natural resistance to the marine borer *Limnoria quadripunctata*: The role of leachable and non-leachable factors. *Holzforschung* 62(1): 99-111. DOI: 10.1515/HF.2008.015

- Chambers JQ, Higuchi N, Schimel JP, Ferreira LV, Melack JM (2000) Decomposition and carbon cycling of dead trees in tropical forests of the central Amazon. *Oecologia* 122(3): 380-388. DOI: 10.1007/s004420050044

- Cunningham AB (2016) Trade study of selected east African timber production species, in: Proceedings of the Convention on International Trade in Endangered Species of Wild Fauna

and Flora Seventeenth Meeting of the Conference of the Parties, Johannesburg, South Africa. pp. 27-66.

- Donnelly BJ, Donnelly DMX, O'Sullivan AM, Prendergast JP (1969) *Dalbergia* species VII, Isolation and structure of melanoxin a new dihydrobenzofuran from *Dalbergia melanoxylon* Guill. and Perr. (Leguminoseae). *Tetrahedron* 25(18): 4409-4414. DOI:10.1016/S0040-4020(01)82981-1

- Donnelly DMX, O'Reilly J, Whalley WB (1975) Neoflavanoids of *Dalbergia melanoxylon*. *Phytochemistry* 14(10): 2287-2290. DOI: 10.1016/S0031-9422(00)91118-X

- Hamada J, Pétrissans A, Ruelle J, Mothe F, Colin F, Pétrissans M, Gérardin P (2018) Thermal stability of Abies alba wood according to its radial position and forest management. *European Journal of Wood and Wood Products* 76: 1669-1676. DOI: 10.1007/s00107-018-1353-5

- Japan Wood Research Society (2000) *Woody Science Experimental Menu.* Buneido Publishing Co. Ltd., Kyoto, Japan. pp. 92-97.

- Lemmens RHMJ (2007) *Xeroderris stuhlmannii* (PROTA) (https://uses.plantnet-project.org/en/*Xeroderris_stuhlmannii*_(PROTA)), Accessed 8 October 2019.

- Malimbwi RE, Luoga EJ, Hofstad O, Mugasha AG, Valen JS (2000) Prevalence and standing volume of *Dalbergia melanoxylon* in coastal and inland sites of southern Tanzania. *Journal of Tropical Forest Science* 12(2): 336-347.

- Miya M, Ball SMJ, Nelson FD (2012) *Drivers of Deforestation and Forest Degradation in Kilwa District*, Mpingo Conservation & Development Initiative, Lindi, Tanzania.

- Mburu F, Dumarçay S, Gérardin P (2007) Evidence of fungicidal and termicidal properties of *Prunus africana* heartwood extractives. *Holzforschung* 61(3): 323-325. DOI: 10.1515/HF.2007.043

- Nakai K, Ishizuka M, Ohta S, Timothy J, Jasper M, Lyatura NM, Shau V, Yoshimura T (2019) Environmental factors and wood qualities of African blackwood, *Dalbergia melanoxylon*, in Tanzanian Miombo natural forest. *Journal of Wood Science* 65(39): 1-11. DOI: 10.1186/s10086-019-1818-0

- Ohmura W, Doi S, Aoyama M, Ohara S (2000) Antifeedant activity of flavonoids and related compounds against the subterranean termite *Coptotermes formosanus* Shiraki. *Journal of Wood Science* 46(2): 149-153. DOI: 10.1007/BF00777362

- Ohmura W, Momohara I, Kiguchi M, Yoshimura T, Takematsu Y, Gensai H, Nomura T, Kaneda T, Saegusa M, Maeda S, Tanikawa M (2011) Anti-termite performance of Japanese and foreign timber species under different degradation environments **(in Japanese)**. *Mokuzai Gakkaishi* 57(1): 26-33. DOI: 10.2488/jwrs.57.26

- Schultz TP, Nicholas DD (2000) Naturally durable heartwood: Evidence for a proposed dual defensive function of the extractives. *Phytochemistry* 54(1): 47-52. DOI: 10.1016/s0031-9422(99)00622-6

- Sekine N, Ashitani T, Murayama T, Shibutani S, Hattori S, Takahashi K (2009) Bioactivity of latifolin and its derivatives against termites and fungi. *Journal of Agricultural and Food Chemistry* 57(13): 5707-5712. DOI: 10.1021/jf900719p

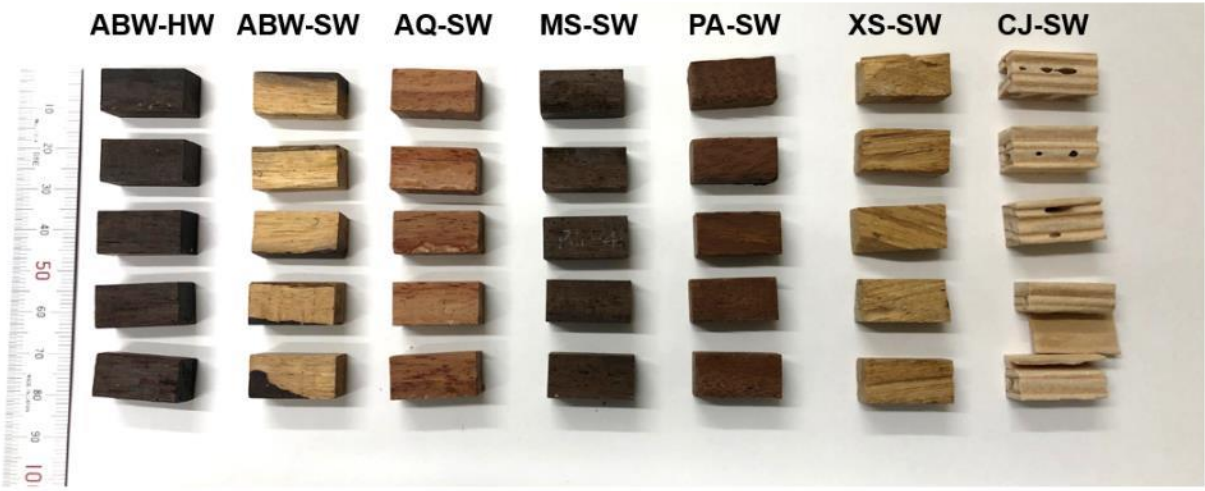
- Seshadri TR (1972) Polyphenols of *Pterocarpus* and *Dalbergia* woods. *Phytochemistry* 11(3): 881-898. DOI: 10.1016/S0031-9422(00)88430-7

- Tascioglu C, Yalcin M, Sen S, Akcay C (2013) Antifungal properties of some plant extracts used as wood preservatives. *International Biodeterioration & Biodegradation* 85: 23-28. DOI: 10.1016/j.ibiod.2013.06.004

- Yin X, Huang A, Zhang S, Liu R, Ma F (2018) Identification of three *Dalbergia* species based on differences in extractive components. *Molecules* 23(9): 1-11. DOI: 10.3390/molecules23092163

4.6. Appendices

Appendix 4.1 Wood samples after exposure to termite test.



Appendix 4.2 ABW-HW samples after exposure to decay test.

Appendix 4.2 ABW-SW samples after exposure to decay test.

Appendix 4.3 AQ-HW samples after exposure to decay test.

Appendix 4.4 MS-HW samples after exposure to decay test.

Appendix 4.5 PA-HW samples after exposure to decay test.

Appendix 4.6 XS-HW samples after exposure to decay test.

Appendix 4.7 CJ-SW samples after exposure to decay test.

CHAPTER 5

GENERAL CONCLUSIONS

These studies indicated the potential of African Blackwood (ABW) to be a valuable tree species in local community forestry. As mentioned above, the utilization of ABW strongly depends on the musical instrument industry; thus the followings must be realized in order to achieve a sustainable forest: (1) continuous cultivation of high-quality timber meeting the requirements for the woodwind production process; and (2) efficient usage of present stock resources. The conclusions in this study contribute to the achievability of these tasks.

According to the results of Chapter 2, ABW trees can survive under various environmental conditions. Growth form including tree appearance, was strongly affected by surrounding vegetation and soil conditions, whereas the physical properties of standing trees were hardly affected by such environmental factors. The conclusions in this chapter study indicated that the cultivation of high-quality ABW trees was fundamentally possible by managing tree appearance. Various factors can affect tree appearance in natural forest. In general, species composition in natural forest is strongly related to topography and human activities, such as forest fire. Topographic characteristics tend to influence the soil conditions and human activities including log harvesting cause forest disturbance. Although the effects of forest fire, which can seriously disturb forest condition, were not studied in the survey, they would affect timber quality. Further study should focus on controlling forest disturbances in terms of establishing suitable forest management system including both fire control and harvesting plans.

In Chapter 3, the potential of wood flow forming was indicated to efficiently use wasted ABW timbers. Since most timbers are normally wasted in the material production process, the results could contribute to the development of another industry, in addition to improving the current usage efficiency of ABW timbers. In particular, the air-dried ABW heartwood could be flowed without any resin impregnations due to highly concentrated extractives. It was suggested that wasted ABW timbers might be used and molded as valuable products, such as parts for musical instruments, by installing a simple production process. In the present production process of woodwinds, the larger volume of high-quality timber is required for the bell parts. Molding of the parts could greatly improve timber usage, and such valuable production would have a significant impact on local industry. Wood flow forming can mold three-dimensional products from bulk wood by plastic flow deformation, and the molding process is flexible against shapes of bulk wood. Since the shapes of

wasted timber in sawmill factories are absolutely varied, it is quite difficult to use them for other new products. Wood flow forming can address such issues.

In Chapter 4, the biological performance of ABW and other local species were clarified in the laboratory tests. The high performance of the species demonstrated its potential for uses beyond current practice. While the performance of ABW heartwood was higher than the other species, some local species, such as *Millettia sthulmannii* and *Pterocarpus angolensis*, showed an even higher biological performance than ABW heartwood. The high performance of ABW heartwood makes it especially useful for new products made from wasted timbers by wood flow forming. High-durability materials are required for woodwinds due to challenging operating conditions (*e.g.*, very wet conditions inside the wooden tube). Both *Millettia sthulmannii* and *Pterocarpus angolensis*, which co-exist with ABW trees in local forest, could contribute to promoting local forestry in terms of increasing valuable species in addition to ABW. Furthermore, systematic harvesting could improve forest conditions focusing on the cultivation of high-quality trees.

Consequently, the obtained results from the study can enhance the establishment of the sustainable forest business model. ABW is expected to become an even more valuable species for local communities in semi-dry areas of African countries. The survivability of ABW under various conditions suggests a potential planting business could be successful even in low resource stock areas. Furthermore, since the physical properties was not affected by growth conditions, planted trees are potentially used as timber material with equivalent properties including biological performance to musical instruments' material. The wasted ABW can be reused *via* novel molding technique such as wood flow forming. The current value of ABW should be sustained and maximized by managing the value chain, and a sustainable and healthy forest is definitely needed given recent concerns. This forest should be based on sustainable forest utilization, supported by the well-established timber market that can continuously provide benefits to local forestry. Thus, forest management should focus on producing valuable timber. To achieve this goal, the stakeholders must create a business model that maximizes each benefit. This study was intended to address the gap between resource supply and global demand. Further steps should be considered to conserve this valuable resource for future generations.

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