Studies on variation of wood properties in plantation-grown teak (*Tectona grandis* L.f.) in Indonesia

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チーク（*Tectona grandis* L.f.）植林木の
木材性質の変異に関する研究

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Chapter 1 Introduction

1.1 Significance of teak plantation forestry in Indonesia

Teak (*Tectona grandis* L.f.) was firstly introduced from India to Indonesia especially in Java Island, during the 14th century by the Hindus (Simatupang 2000a; Siswamartana 2005). Then, teak was extensively planted in Java Island under the control of Sultans in 15th century. With the arrival of the Portuguese in 15th century and the Dutch in 17th century, the demand for the durable teak timber for general construction and ship building intensified. By 1748 the Dutch East India Company controlled all teak forests and monopolized teak trading. Influenced by three German foresters, all the Javanese teak forests were brought under regular management in the late of 1800s. The taungya regeneration method was also introduced in 1873, and since 1895 almost all teak forests have been regenerated by this system. Taungya is a system in which farmers plant tree seeds or seedlings to establish a forest plantation and in association with their food crops (Evans and Turnbull 2004).

Nowadays, teak plantation in Indonesia is categorized into two types, state forests (in Java and outside of Java) and small-scale plantations/community forests (Siswamartana 2005). State forest is that grown on the state land. At present, about 90% of teak forest grown on the state land in Indonesia is located in Java Island, which is managed by a government forest enterprise, i.e. “Perum Perhutani”. Total teak plantation in Indonesia is 1,269,000 ha (Kollert and Cherubini 2012). In 2013, total area of Perum Perhutani was 2,522,253 ha, consisting of 1,829,502 ha of forest production area and 692,751 ha of forest conservation area (Suhaendi 1998; Perum Perhutani 2014a). Among the total area of forest production, 60% is occupied by teak and other 40% is dominated by *Gmelina arborea*, *Acacia mangium*, *Falcataria moluccana*, *Switenia mahogany* etc. (Siswamartana 1998; Perum Perhutani 2014a). In the other islands of Indonesia (Sulawesi, Sumbawa, Maluku, and Sumatra), teak forests are managed by local governments and local communities. Furthermore, in Indonesia, small-scale plantation is also established by the local communities in the private lands in Java and outside of Java Island (Siswamartana 2005). These small-scale plantations are called “community forests”. In the community forest, teak is also selected as plantation species, because its wood has high value. Teak community forest became common on Java Island in 1960s. By the 1980s, teak production was regarded as an attractive alternative source of living hood. Furthermore, community forest teak production has become an important source of raw material for teak wood industry and income for the rural family (Roshetko *et al.* 2013).

The total of the industrial demand for teak timber in Indonesia is estimated to about 1.5 to 2.2 million m^3 per year (Roda *et al.* 2007). In 2012, a government forest enterprise, Perum Perhutani, which is the largest manager of teak plantations in Java, produced 403,432 m^3 of teak, and most of produced wood resources were sold to the commercial teak wood industry (Perum Perhutani 2012). After 1985, supply of teak wood decreased almost every year (Mawardi 2012). Until now, supply of wood including teak and other species is not enough to fulfill the demand of wood industries in Indonesia. The increase in wood demand is about 13 – 17% every year, caused by increasing number of the human population in Indonesia (Mawardi 2012). Therefore, the shortage of the supply of teak wood is a serious problem for wood industry in Indonesia. To solve the unbalance of demand and supply of the wood, more efficient forestry system is needed for teak wood production in Indonesia.

1.2 General features of teak

1.2.1 Botany and ecology

Teak (*Tectona grandis* L.f.) belongs to family Lamiaceae. Teak is a tree native to the monsoon regions in India, Myanmar, Laos, and Thailand (Bermejo *et al.* 2004; Robertson and Reilly 2005; Ogata *et al.* 2008; Palanisamy *et al.* 2009). It has also been introduced to Indonesia, Malaysia, Sri Lanka, Africa, South America, Central America, and Australia (Palanisamy *et al.* 2009). In Indonesia, teak plantation spreads in Java, Sulawesi, Sumbawa, Maluku, and Sumatra (Martawijaya *et al.* 2005).

The size of teak tree ranges from medium to large to 50 m in height, and has straight bole, with a diameter up to 150 – 250 cm (Fig. 1.1A), sometime fluted or with low buttresses at base, bark surface with longitudinal cracks and grayish-brown color (Fig. 1.1B), and leaves with broadly ovate (Fig. 1.1C) (Soerianegara and Lemmens 1994). Traditionally, teak plantations are managed on rotations of 60-80 years (Lukmandaru and Takahashi 2008; Niamké *et al.* 2011).

Teak naturally occurs in the various types of tropical deciduous forest. The various teak forest formations can be categorized into three main types: moist natural formation (annual rainfall of 1300 – 2500 mm), dry natural formation (annual rainfall of 760 – 1500 mm), and Indonesian formation (annual rainfall of 1200 – 2000 mm) (Soerianegara and Lemmens 1994). Optimal growth is attained with an annual rainfall of 1200 – 2500 mm of which 75% falls in the rainy season. The altitudinal limit lies around 1000 m (Soerianegara and Lemmens 1994). In Indonesia, especially on the Java Island, teak grows at elevations of 100 – 700 m (Bailey and Harjanto 2005). The most suitable soil is a deep and well-drained, fertile alluvial-colluvial soil with pH of 6.5 – 8.0 and relatively high calcium and phosphor contents (Soerianegara and Lemmens 1994).

1.2.2 Wood

Teak produces well-known and very good general-purpose timber. Its favorable properties make it suitable for a wide variety of purposes. In the past time, it was extensively used for deck houses, rails, latches, weather door etc. Other applications of teak are building poles, transmission line poles, fence posts, wall boards, beams, woodwork, boxes, musical instruments, toys, railway sleeper, and railcar construction. Recently, teak is used in housing, particularly suitable for interior and exterior joinery (windows, solid panel doors, framing), and floors exposed to light. It is also used quite extensively for the manufacture of house and garden furniture (Soerianegara and Lemmens 1994, Martawijaya *et al*. 2005; Niamké *et al*. 2011).

The wood is semi ring-porous in natural trees growing in the regions with alternating dry and wet seasons. Sapwood color is pale yellowish white to pale yellowish brown. Heartwood color is dull golden brown when it is fresh, turning gradually brown to dark brown on exposure to the light, often with black brown streaks on the longitudinal surfaces. In the wood from plantation trees (Figs. 1.2 and 1.3), especially those planted in the region without distinct dry season, heartwood color is usually paler than that of natural trees, yellowish brown, often with greenish tinge, and with less pronounced ring porosity (Soerianegara and Lemmens 1994; Ogata *et al*. 2008).

Air-dry density is 0.56 – 0.75 g/cm^3, with relative small variation, mostly between 0.60 – 0.70 g/cm^3. The difference of wood density between is not very great between natural trees and plantation (Ogata *et al*. 2008). Soerianegara and Lemmens

(1994) reported that at 12% moisture content the modulus rupture, modulus of elasticity, compression parallel to grain, and compression perpendicular to grain are 85 – 106 MPa, 10.0 – 13.4 GPa, 47 – 60 MPa, and 6.0 – 7.5 MPa, respectively (Soerianegara and Lemmens 1994).

Vessel is predominantly solitary, some in multiples of 2 – 3 (– 6); maximum tangential diameter of earlywood solitary vessels is 300 – 400 µm in ring-porous wood, 200 – 250 µm in diffuse-porous wood, and maximum diameter of latewood vessel is 50 – 290 µm (Fig 1.3C). Fibers exclusively septate with 2 to several septa per fiber; fiber length, fiber tangential diameter, and fiber wall thickness are 1.1 – 2.0 mm, 10 – 25 µm, and 3 – 5 µm, respectively (Soerianegara and Lemmens 1994; Ogata *et al*. 2008).

The wood contains 47.5% cellulose, 30% lignin, 14.5% pentosan, 1.4% ash, and 0.4 – 1.5% silica; the solubility is 4.6% in alcohol-benzene, 1.2% in cold water, 11.1% in hot water, and 19.8% in a 1% NaOH solution, respectively (Soerianegara and Lemmens 1994). Narayanamurti *et al.* (1962) reported that total ethanol and methanol extract contents at the inner heartwood of 10-, 30-, and 62-year old teak trees from India were 6.5 – 6.6%, 6.3 – 7.4%, and 5.5%, respectively. The total petroleum-ether, acetone/water, and ethanol/water extract contents at the outer heartwood of 29-year-old teak trees were 8.8 – 9.4% (Haupt *et al*. 2003). Bhat *et al.* (2005) reported that total ethanol-benzene extract content was 12.4 – 16.0% in 35-year-old teak planted in India. Lukmandaru *et al.* (2009) reported that the values of n-hexane, ethyl acetate, methanol, cold water, and hot water extract contents of 32-year-old teak trees planted in Indonesia were 3.3 – 4.1%, 1.2 – 1.6%, 2.0 – 2.6%, 1.3 – 1.4%, and 2.4 – 2.6%, respectively. They also found that total extract content with ethanol-benzene in the outer heartwood of 8-, 30-, and 51-year-old teak trees planted in Indonesia were 5.3, 7.0, and 8.0%, respectively (Lukmandaru and Takahashi 2009).

It is known that teak wood has natural durability against fungal and insect attacks (Rudman *et al*. 1967; Yamamoto and Hong 1989; Thulasidas and Bhat 2007; Lukmandaru and Takahasi 2008, Lukmandaru *et al.* 2009). The mass loss of 35-year-old teak wood attacked by a brown-rot fungus *Polyporus palustris* and a white-rot fungus *Trametes versicolor* were 18.4 – 43.3% and 1.7 – 1.9%, respectively (Bhat *et al*. 2005). The mass losses of teak wood in the inner heartwood attacked by the white-rot fungus *T. versicolor* (Syn. *Coriolus versicolor*) were 54, 55, and 8% for 13-year-old teak trees planted in New Guinea, 14-year-old teak trees planted in Indonesia, and 168-year-old teak trees planted in Burma, respectively (Rudman *et al.* 1967). Yamamoto *et al.* (1998) reported that mass loss at the heartwood part attacked by *T. versicolor* in 30-year-old teak trees planted in Malaysia was 3.2%. In addition, another study reported that mass losses of the heartwood part attacked by *T. versicolor* were 11.0, 11.8, and 7.6% respectively for 13-, 21-, and 55-year-old teak trees planted in India (Bhat and Florence 2003). In general, the older tree has higher natural durability than the younger age in teak trees.

1.3 Tree breeding for wood properties

1.3.1 Significance of tree breeding for wood properties

Wood is a very variable substance with differing among species and genera, among geographic sources within a species, and among trees with a geographic source as well as within each individual tree (Panshin and de Zeeuw 1980; Zobel and van Buijtenen 1989). Furthermore, tree-to-tree variability is especially large, with differences within a species often under strong genetic control (Zobel and van Buijtenen 1989; Zobel and Jett 1995; White *et al.* 2007). On the other hand, for many years, tree improvement programs only included growth, form, adaptability, and pest resistance in their assessments while did not include wood properties (Kedharnath *et al.* 1963; Zobel and van Buijtenen 1989; Costa e Silva *et al.* 1994; Kjaer *et al.* 1999; Zobel and Jett 1995; Goh *et al.* 2007). With the large variability of the wood properties within the trees, the high possibility was arisen to improve wood quality and produce more uniform and usable wood products. Therefore, wood quality improvement should be included as an integral part of the breeding programs (Kedharnath *et al.* 1963; Zobel and van Buijtenen 1989; Zobel and Jett 1995; Ishiguri *et al.* 2007; Pedersen *et al.* 2007).

1.3.2 Evaluation methods of genetic variances and heritabilities

The total variance is the phenotypic variance, or the variance of phenotypic values, and is the sum of the separate components (genetic and environmental factors) (Falconer 1989, Zobel and Jett 1995). Thus, the total variances with certain qualifications are

$$\sigma^2_P = \sigma^2_G + \sigma^2_E$$
$$= \sigma^2_A + \sigma^2_D + \sigma^2_I + \sigma^2_E$$

Where, σ^2_P denotes the variance of phenotypic values, σ^2_G the total variance of genotypic value, σ^2_A the variance of additive/breeding value, σ^2_D the variance of dominance value, σ^2_I the interaction variance, and σ^2_E variance of environmental values, respectively. There are two certain qualifications, the first, the genotypic values and environmental deviations may be correlated, and the second, there may be interaction between genotype and environment (Falconer 1989).

Although heritability is generally used relative to genetic differences among individuals within a given population of a species, it is also occasionally applied to populations, such as families, provenances, and rarely, even different species. However, heritability is nothing more than a ratio that expresses the degree to which a characteristic is passed from parent to offspring (Zobel and Jett 1995). Two commons measures of the relative amount of genetic control for a given trait in a population are the broad-sense heritability (H^2) and narrow-sense heritability (h^2) (Falconer 1989, Zobel and Jett 1995; White *et al*. 2007). The H^2 (or repeatability, R) is the ratio of the total genetic variance to the total phenotypic variance:

$$H^2 = \sigma^2_G / [\sigma^2_G + \sigma^2_E]$$
$$= (\sigma^2_A + \sigma^2_D + \sigma^2_I) / [(\sigma^2_A + \sigma^2_D + \sigma^2_I) + \sigma^2_E]$$

The h^2 is the ratio of the additive genetic variation to the total phenotypic variation:

$$h^2 = \sigma^2_A / [(\sigma^2_A + \sigma^2_D + \sigma^2_I) + \sigma^2_E]$$

Both h^2 and H^2 are trait-, population-specific, and also greatly influenced by homogeneity of the environment containing the genetic test condition. Further, true heritabilities, which are never known, must be estimated from field experiments employing offspring (clonal offspring for estimation H^2 and sexual offspring for estimation h^2). In general, heritablities are difficult to estimate and require large numbers of clones and/or families for precise estimates (White *et al*. 2007).

1.3.3 Heritability of growth characteristics and wood properties in hardwoods

In forest tree population, heritability estimates have been calculated for many traits, such as those reflecting physiological processes, phenology of annual growth and flowering, stem growth, and wood quality (White *et al*. 2007). In general, the h^2 for many stem growth and form traits range from 0.10 – 0.30, while for wood specific gravity (wood density) they range from 0.3 – 0.6 in softwood and hard wood (White *et al*. 2007). The genetic control for growth traits is lower than that for wood traits, because growth is a polygenic trait strongly influenced by environment (Hein 2011). Hai *et al*. (2008) reported that clonal R ranged from 0.28 – 0.47 for height, 0.21 – 0.56 for diameter at breast height, 0.21 – 0.54 for stem volume, 0.21 – 0.32 for straightness, and 0.21 – 0.28 for branch thickness in *A. auriculiformis* planted in Vietnam. In addition, the h^2 of height, diameter, stem form, and bark thickness were 0.33, 0.40, 0.54, and 0.18, respectively for *A. mangium* planted in Indonesia (Susanto *et al*. 2008). The h^2 of stem diameter and tree height ranged from 0.16 – 0.33 in *Eucalyptus* spp. (Muneri and Raymond 2000; Pelletier *et al*. 2008; Costa e Silva *et al*. 2009).

Genetic control of most wood properties is moderate to very strong. Wood variation results from environmental differences, genetic differences, and their interaction (Zobel and Jett 1995). However, genetic improvement of wood has focused on manipulating density with limited emphasis on other traits (Zobel and Jett 1995). Wood density is an important wood property for both solid wood and fiber products in both conifers and hardwoods. It is absolutely the single most important wood property because of its strong relationship to both of yield and quality as well as its large variance and high heritability (Zobel and Jett 1995; Hein 2011). The h^2 and H^2 of wood density were 0.18 and 0.47, respectively in *A. auriculiformis* (Susanto *et al.* 2008; Hai *et al*. 2010). In *Eucalyptus* spp., the h^2 for wood density was 0.33 – 1.00 (Muneri and Raymond 2000; Santos *et al*. 2004; Pelletier *et al*. 2008; Hein 2011). In addition, only a few researches have been conducted on mechanical properties in hardwood breeding program. Hai *et al*. (2010) reported that clonal R for modulus of elasticity and modulus of rupture in *A. auriculiformis* were 0.57 and 0.29, respectively. In *E. grandis*, h^2 of compressive strength parallel to grain and static bending were 0.57 and 0.50, respectively (Santos *et al*. 2004).

Except most for wood density, the inheritance of fiber length has been studied intensively for wood property in the hardwood because it is often considered as the limiting factor in their use. Fiber length has been reported to have moderate to strong heritabilities. However, of all wood properties, fiber length is affected rather strongly by both genetic and environment. Fiber diameter and wall thickness are reasonably strongly inherited, though they are closely related to specific gravity, separate genetic breeding is rarely applied for them. The vessel also has a strong inheritance (Zobel and Jett 1995). The H^2 of fiber length, fiber diameter, fiber wall thickness, and vessel diameter were 0.14 – 0.61, 0.35, 0.50, and 0.22, respectively in *P. deltoides* (Klasnja *et al*. 2003; Pande and Dhiman 2011).

Extractive is usually strongly inherited, whereas there is a few studies showing the low inheritance value (Zobel and Jett 1995). The H^2 values of extractive content were 0.18 and 0.99 in *P. tremuloides* and *P. deltoides*, respectively (Yanchuk *et al*. 1988; Klasnja *et al*. 2003). In addition, h^2 of extractive content was 0.28 – 0.54 in *E. urophylla* (Denis *et al*. 2013). Furthermore, h^2 of extractive content was reported to be moderate value (0.35) in *E. globulus* (Poke *et al*. 2006).

Although wood color is generally thought to be influenced by the environment, reasonably strong genetic component has been found for some species (Zobel and Jett 1995). Genetic control of wood color was reported to be controlled less genetically in *Quercus* spp. (Mosedale *et al*. 1996). The variation of wood color of *E.* dunii was low, while significant difference was found among half-sib family (Vanclay *et al*. 2008). Montes *et al*. (2008) reported that h^2 values of brightness (L^*), yellowness (a^*), and redness (b^*) were 0.48, 0.52, and 0.52, respectively for *Calycophyllum spruceanum*. In teak wood color, the H^2 values of L^*, a^*, and b^* were 0.45, 0.36, and 0.36, respectively (Moya and Marín 2011).

1.3.4 Evaluation methods of wood properties in tree breeding programs

Though assessing wood properties for selection and breeding programs requires the investigation in a large number of family/clone, a sufficient number is still limited. In fact, it is very difficult to cut the sample trees in a large number. In addition, traditional methods of assessment are not only costly but also they cause the destruction of the sample trees and the loss of genetic materials (Raymond and

MacDonald 1998; Muneri and Raymond 2001; Pelletier *et al.* 2008). These factors are promoting the development and evaluation of non-destructive methods for assessing wood quality (Pelletier *et al.* 2008). In the present study, the following semi- or non-destructive evaluation methods for wood properties were applied to evaluate the among-clone or -family variation in wood properties of teak.

1.3.4.1 Stress-wave velocity

The stress-wave method is a well-known non-destructive method for evaluating wood quality. Stress-wave propagation in wood is a dynamic process which is internally related to the physical and mechanical properties of wood. Several different types of waves can propagate in wood structure, such as longitudinal, shear, and surface waves. Of these waves, longitudinal travel fastest and are the most commonly used to evaluate wood properties (Wang *et al.* 2000, 2001; Ishiguri *et al.* 2007, 2008, 2013; Wu *et al.* 2011). One of the commercial stress-wave devices used widely is FAKOPP micro second timer. It was developed in Hungary, shows promise for use on standing trees and hence is suitable for screening progenies (Jayawickrama 2001; Kumar *et al.* 2002). This device measures the transit time of a stress-wave between two transducers (Bucur 2006; Brashaw *et al.* 2009). There is a significant, positive relationship between the SWV of standing trees or logs and the Young's modulus of logs (Nanami *et al.* 1993; Ross *et al.* 1997; Ikeda and Arima 2000; Wang *et al.* 2001; Dickson *et al.* 2003; Ishiguri e*t al.* 2007, 2008, 2013; Wu *et al.* 2011).

SWV has also been used to evaluate the mechanical properties, such as stiffness in the breeding program (Jayawickrama 2001; Kumar *et al.* 2002; Wu *et al.* 2011; Hidayati *et al.* 2013a,b). Jayawickrama (2001) reported that combining stress-wave results with density and branch cluster frequency could well be a viable and cost-effective way to select progenies for clearwood stiffness in the juvenile wood zone in pine. In addition, the h^2 of the SWV was 0.46 for radiata pine progeny test in New Zealand (Kumar *et al.* 2002). In 4.3-year-old *Eucalyptus* spp. planted in Southern China, SWV was significantly different among 23 clones (Wu *et al.* 2011).

1.3.4.2 Pilodyn penetration

The Pilodyn wood tester is an instrument originally developed in Switzerland for determining the degree of soft rot in wooden telephone poles (Taylor 1981; Moura *et al*. 1987; Hansen 2000). A Pilodyn is a hand-held instrument which fires a flat-nosed pin into a tree with a fixed force (Taylor 1981; Sprague *et al*. 1983; Nicholls 1985; Greaves *et al*. 1996; Raymond and MacDonald 1998; Hansen 2000). The depth to which the pin penetrates is indicated on the instrument and is inversely proportional to the density of wood. Negative correlations have been reported between Pilodyn penetration and wood density (Taylor 1981; Moura *et al*. 1987; King *et al*. 1988; Wei and Borralho 1997; Iki *et al*. 2009; Wu *et al*. 2010, 2011).

Pilodyn was introduced as a non-destructive assessment of density in tree breeding program (Sprague *et al*. 1983; Moura *et al*. 1987; King *et al*. 1988; Woods *et al*. 1995; Hansen 2000). Pilodyn sampling is a faster, cheaper, and non-destructive method, resulting in overall higher expected gains for selection on trees or culling of seedling seed orchard in comparison with the more destructive direct assessment of density (Greaves *et al*. 1996). Up to date, many researchers have used Pilodyn tester for evaluating wood density in the tree breeding program (Sprague *et al*. 1983; Moura *et al*. 1987; Costa e Silva *et al*. 1994; Hansen and Roulund 1997; Raymond and MacDonald 1998; Wei and Borralho 1997; Iki *et al*. 2009; Wu *et al*. 2010, 2011). Sprague *et al*. (1983) reported that Pilodyn penetration was significantly different among provenances of *Eucalyptus* spp. planted in Australia and Timor. The R of 5-year-old *E. camaldulensis* was 0.69 – 0.77 planted in Australia (Raymond and MacDonald 1998). Pilodyn penetration was significantly different among 22 clones of 4.7-year-old *Eucalyptus* spp. planted in China (Wu *et al.* 2010). In addition, Pilodyn penetration was also reported to be significantly different among 23 clones of 4.3-year-old *Eucalyptus* spp. planted in Southern China (Wu *et al*. 2011).

1.3.4.3 Increment core

Increment core is the most common form of non-destructive sampling, and it has long been used for growth assessments, for dendrochronology, and to establish forest stand history (Pelletier *et al.* 2008). However, this method causes a small destruction in the tree. Therefore, it is more proper that this method should include semi-destructive method of wood property evaluation (Ishiguri *et al.* 2012).

More recently it has been used to asses some wood properties in softwoods and hardwoods, employing a wide range of methods. Basic density, pulp yield, grain angle, latewood proportion, extractive content, tracheid length, and reaction wood proportion have been measured with increment cores by direct measurements (Mosedale *et al*. 1996; Wei and Borralho 1997; Muneri and Raymond 2000, 2001; Klasnja *et al.* 2003; Poke *et al*. 2006; Pelletier *et al*. 2008; Bush *et al*. 2011; Wu *et al.* 2010, 2011; Makino *et al*. 2012; Ishiguri *et al.* 2012), dissection (Klasnja *et al*. 2003; Pande 2011; Pande and Dhiman 2011; Ishiguri *et al*. 2012), macerated (Kedharnath *et al*. 1963; Muneri and Raymond 2001; Klasnja *et al*. 2003), image analysis/X-ray analysis (Nocetti *et al*. 2011), and near-infrared reflectance analysis (Costa e Silva *et al*. 1994; Poke *et al*. 2006; Denis *et al*. 2013).

1.4 Literature review for tree breeding of teak

Teak breeding programs have started in some Southeast Asian countries, such as Thailand, Indonesia, Papua New Guinea, and Malaysia (Soerianegara and Lemmens 1994; Perum Perhutani 2000; Monteuuis *et al.* 2011). Selection of plus trees with the establishment of clonal test sites, provenance trial sites, and progeny trial sites has been employed. However, most of these programs only focuses growth characteristics, such as stem diameter, tree height, volume, flowering, stem straightness, and pest resistance (Callister and Collins 2008; Monteuuis *et al*. 2011).

1.4.1 Tree breeding programs of teak in Indonesia

Teak breeding and improvement programs in Indonesia have started in 1981 by Perum Perhutani with the objective of increasing the productivity of teak plantations using genetically superior seed, identifying the most suitable provenances for particular areas, improving the genetic properties of trees with regard to growth, stem form, branching, and resistance to pest and disease (Siswamartana 1998; Suseno 2000; Perum Perhutani 2000). These programs expected that all teak plantations will be established using genetically improved seeds in the future (Suseno 2000). Furthermore, the use of better planting material combined with proper silvicultural practice is expected to reduce the time needed to achieve commercial stem diameter (Siswamartana 2005).

The tree breeding and improvement strategy is implemented by establishing seed production areas, utilizing plus trees for clonal seed orchard (CSO) establishment, hedge garden, and tissue culture propagation. These implementations are to supply adequate improved teak wood, seeds, and seedlings. Seed production areas are established from the existing teak plantation. The stands are selected based on tree phenotype (stem diameter, tree height, stem form, etc.). The collected seeds in the seed production area are used for operational plantation. Plus trees are also selected in the existing teak plantation mainly based on growth and stem form. The buds of plus trees are grafted onto the rootstock for establishing clonal seed orchard (CSO). During period of 1983 – 1996, total 1,303 ha of CSOs were established comprising 144 clones. Hedge garden is developed to produce shoot cuttings for low-cost clonal forestry plantation. It was started in 1997. The material used in this garden is derived from mature plus trees. Furthermore, in 1986, tissue culture propagation was started. Tissue culture has developed to produce vegetative seeds from selected teak clones for the establishment of clonal plantation. Though tissue culture technique is expensive, it can produce plating stocks in high quantity in a relative short time (Perum Perhutani 2000). In addition, researches on the teak breeding material in Indonesia have been conducted by some researchers in Indonesia, which mostly focus on growth characteristics (Na'iem 2000; Danarto and Hardiyanto 2000). However, researches on wood quality were very few (Simatupang 2000b, Hidayati *et al*. 2013a, b, 2014).

As product of the teak breeding programs in Indonesia, new type of teak has been obtained with the expected rotation age of 15 – 20 years in order to decrease the rotation age. In Perum Perhutani, this new type of teak is called "Jati Plus Perhutani (JPP)". The source of this JPP comes from two best clones of the breeding programs. From these two clones, new generations were obtained by generative propagation (seed) and vegetative propagation (clone and tissue culture) (Perum Perhutani 2014b). Some private companies have also produced new type of teak as planting material. It is called "Jati Unggul Nusantara (JUN)/jati super/jati prima/jati emas/and jati genjah" (Sumarna 2011). Special preparation of planting site and special treatment were required to gain the best performance of JPP/JUN. Furthermore, the JUN plantation has established in Lampung (Sumatra Island). At 5-year-old, the diameter and height reached to 14 – 20 cm and 10 – 14 cm, respectively (Sumarna 2011). In addition, JUN plantation has been also established in Kulonprogo, Yogyakarta, Java Island in

2011. As the result, at the age of 6-month-old, the tree height reached to 3 m (Atmasari 2012). However, the wood properties of these plantations have not been determined yet.

1.4.2 Growth characteristics

Tree breeding programs for teak have primarily targeted breeding trees with superior growth characteristics (diameter, height, stem form, etc.) and pest resistance (Kedharnath *et al*. 1963; Soerianegara and Lemmens 1994; Kjaer *et al*. 1999; Perum Perhutani 2000; Goh *et al*. 2007).

Swain *et al*. (1999) reported that height and diameter were significantly different among 6 clones of 7- and 8-year old teak planted in India: their h^2 values for height and diameter were 0.38 and 0.28 of 7-year-old, and 0.61 and 0.72 of 8-year-old, respectively. Danarto and Hardiyanto (2000) reported that 142 teak families originating from Java and East Nusa Tenggara, Indonesia and planted in East Java showed significant differences in diameter and its h^2 was 0.23. Stem diameter and tree height at 16-months were found to be significantly different among clones and across sites of teak planted in Indonesia (Na'iem 2000). Height, diameter, and stem straightness were significantly different among 12 provenances of 30-year-old teak trees planted in Tanzania (Pedersen *et al*. 2007). In addition, H^2 values of diameter, height, bole volume, stem straightness, insect defoliation, and flowering in 61 clones of 3.5-year-old teak trees were 0.37, 0.28, 0.35, 0.12, 0.06, and 0.41, respectively (Callister and Collins 2008). Monteuuis *et al.* (2011) reported that significant differences in growth characteristics (diameter, height, bole volume, and fork height) were observed among teak trees originating from 8.8-year-old trees of 42 different genetic sources comprising 26 open-pollinated families from the seedlings planted in Malaysia: the h^2 values of diameter, height, bole volume, and fork height were 0.24, 0.51, 0.34, 0.56, respectively. In addition, Chaix *et al*. (2011) reported the h^2 values of 0.46 and 0.76 for diameter and height, respectively, in 8.7-year-old teak trees from 26 clonal seed orchard families planted in Taliwas, Malaysia.

1.4.3 Wood properties

Basic density was significantly different among 10 clones of teak planted in India (Indira and Bhat 1998). Nocetti *et al.* (2011) reported that significant provenance effect was detected for both wood density and ring anatomical structure (ring porosity index). Percent of heartwood was significantly different among 5 provenances of teak planted in Puerto Rico (Kjaer *et al*. 1999). Wood color (L^*, a^*, and b^*) and dynamic modulus of elasticity were significantly different among 40 clones of teak planted in Costa Rica, and H^2 values of L^*, a^*, b^* and dynamic modulus of elasticity were 0.45, 0.36, 0.36, and 0.34, respectively, in 10-year-old teak trees (Moya and Marín 2011). Furthermore, Simatupang (2000b) stated that the heartwood of desirable mother trees should change into gold yellow after shortly exposing to sunlight, show an even distribution of density from pit to bark, and be free of allergic inducing compounds. In addition, heartwood percentage and basic density were varied among 21 clones of 16-year-old teak trees planted in India (Rao and Shashikala 2005). However, researches on wood quality of teak breeding program in Indonesia are very limited.

1.5 Objectives of the present study

Breeding programs of teak have been developed in order to increase the productivity of wood in Indonesia, because teak is one of the most important long rotation plantation species in the country. However, teak breeding program in Indonesia still only focuses on growth parameters, such as stem diameter, height, stem form, etc. Therefore, it is essential to evaluate the wood property of breeding materials selected already by the growth characteristics. The overall objectives of this study are to evaluate the growth characteristics and wood properties of teak breeding material selected by growth characteristics through the teak breeding programs in Indonesia. The present study, therefore, is designed to clarify the following four points:

i. The variation of growth characteristics and wood properties among 15 teak clones selected by the growth characteristics in Indonesia and the relationships among measured characteristics.

ii. The variation of growth characteristics and wood properties among seed provenances derived from Indonesia and outside of Indonesia, and the relationships among characteristics.

iii. The variation of anatomical characteristics and wood properties among 9 teak clones, the relationships among characteristics, radial variations of measured characteristics, and xylem maturation process.

iv. The variation of decay resistance, heartwood color, extractive content, and the relationships between decay resistance and other measured characteristics.

1.6 Outline of this thesis

Chapter 1 described general situations of teak plantation and teak wood industry in Indonesia. This chapter also reviewed teak breeding program in Indonesia. Theoretical considerations as well as the objectives of the present study were also described in this Chapter.

In Chapter 2, growth characteristics (stem diameter, tree height, and bole volume) and wood properties (stress-wave velocity and Pilodyn penetration) were investigated to clarify the variations among 15 clones planted in Indonesia. In addition, environmental effects on the measured characteristics, interactions between genetic and environmental factors, and the relationships between measured characteristics were also discussed.

Chapter 3 described the variations of growth characteristics (stem diameter, tree height, and bole volume) and wood properties (stress-wave velocity and Pilodyn penetration) among seed provenances. Based on the results, the relationships between measured characteristics and the effectiveness of principal component analysis (PCA) in breeding program of teak were also discussed.

Chapter 4 aimed to clarify the variations of anatomical characteristics and wood properties among nine clones, the relationships between measured characteristics, and radial variations of measured characteristics. In addition, xylem maturation process in teak was also clarified.

In Chapter 5, the variations of decay resistance, heartwood color, and extractive content were investigated for nine clones. From the obtained results, the relationships between decay resistance and other measured characteristics were also discussed.

Based on the results obtained in the present study, Chapter 6 described conclusion of the whole study.

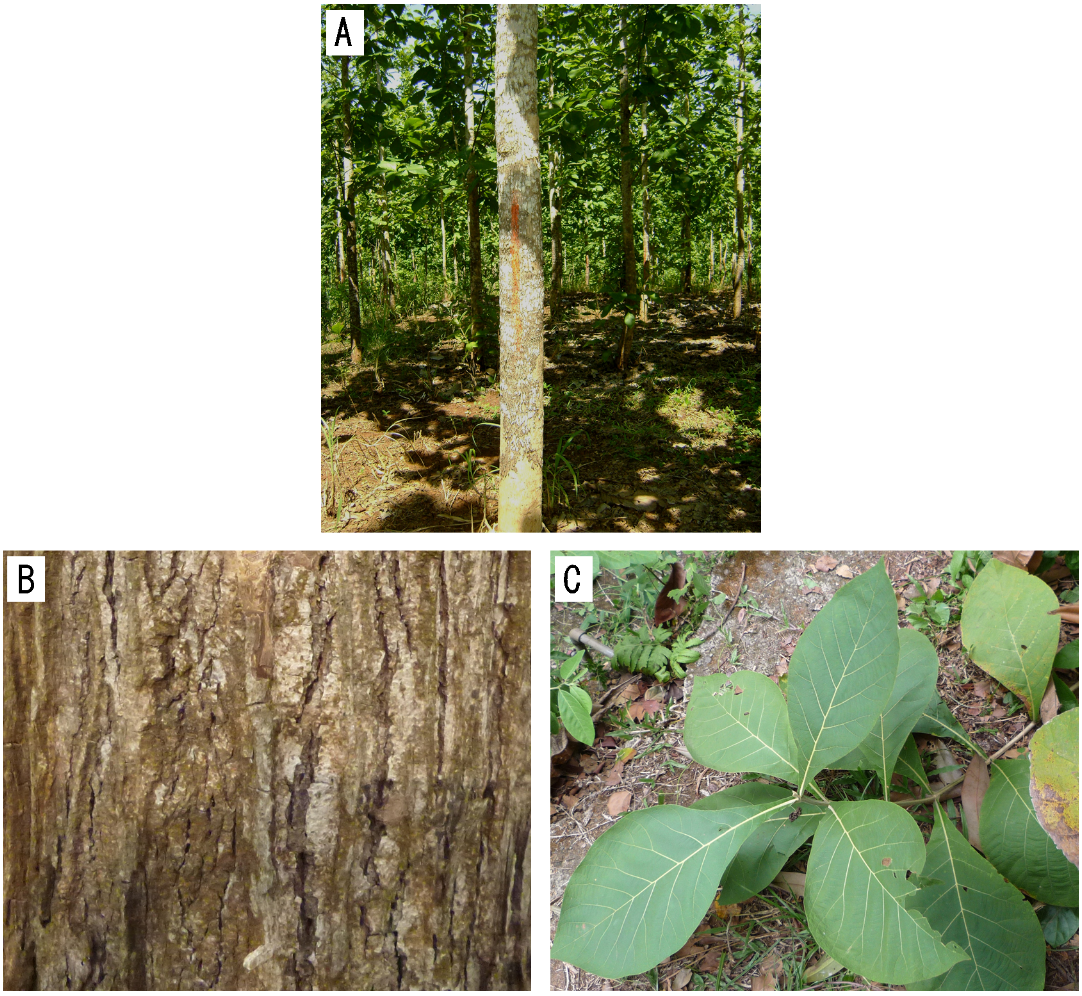


Fig. 1.1 Photographs of teak trees planted in Educational Forest of Wanagama, Gadjah Mada University, Yogyakarta, Indonesia.

Note: A, stem shape; B, bark; C, leaf.

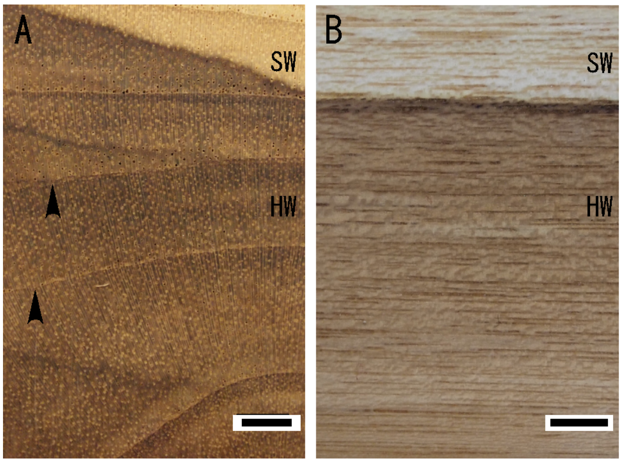


Fig. 1.2 Photographs of teak wood.

Note: A, Transverse section; B, radial section; SW, sapwood; HW, heartwood. Arrowheads indicate growth ring boundary. Scale bar = 5 mm.

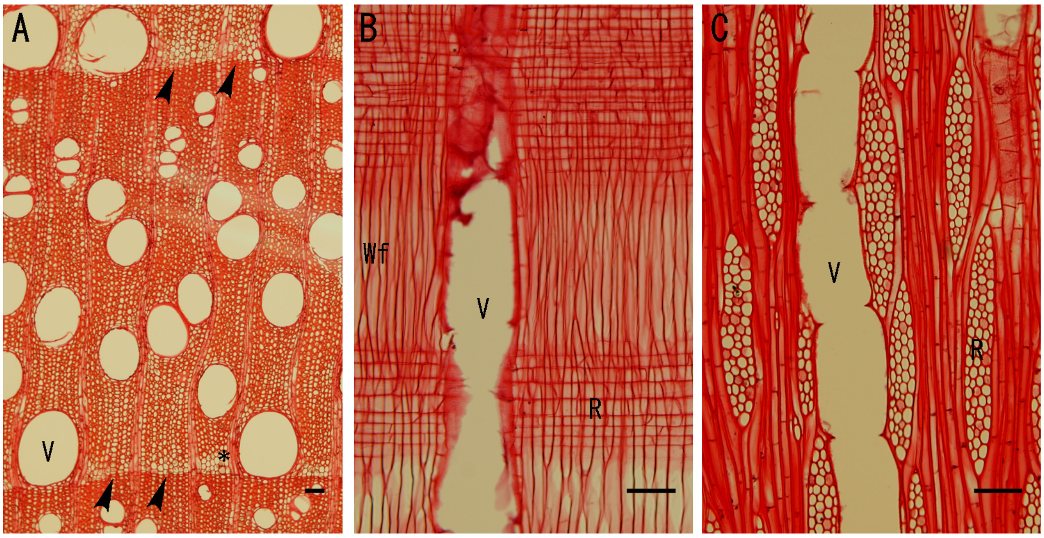


Fig. 1.3 Micrographs of wood section stained with safranin in *Tectona grandis*.

Note: A, Transverse section; B, radial section; C, tangential section; V, vessel element; Wf, wood fiber; R, ray parenchyma cell. Arrowheads and asterisk indicate growth ring boundary and axial parenchyma cell, respectively. Scale bar = 100 µm.

Chapter 2 Growth characteristics, stress-wave velocity, and Pilodyn penetration of 15 clones from 12-year-old teak trees planted at two different sites in Indonesia

2.1 Introduction

Tree breeding programs for teak have been established in Southeast Asian countries for developing more productive teak forests (Soerianegara and Lemmens 1994). Tree breeding programs for teak have primarily targeted breeding of trees with superior growth characteristics, such as diameter, height, stem form, and pest resistance (Soerianegara and Lemmens 1994; Callister and Collins 2008; Monteuuis *et al*. 2011). Zobel and van Buijtenen (1989) pointed out that wood quality improvement should be included as an integral part of the breeding programs. Thus, to date, there has been a focus on improving teak wood properties by tree breeding (Kjaer *et al.* 1999; Moya and Marín 2011; Solorzano *et al.* 2012).

Teak is also an important commercial plantation species in Indonesia. To date, some clones with superior growth characteristics have been selected by the breeding programs in the country. However, only limited information is available concerning the wood properties of teak trees selected by the breeding programs in the country.

In this Chapter, growth characteristics [stem diameter (D), tree height (TH), and bole volume (V)], stress-wave velocity (SWV), and Pilodyn penetration (P) were measured for the 15 clones of 12-year-old teak trees planted at two different sites on the island of Java, Indonesia. Based on the results obtained, the variations in growth characteristics, SWV, and P among clones, R, interaction between genotype and environment, and correlations between growth characteristics, SWV, and P were clarified.

2.2 Materials and methods

2.2.1 Materials

Two hundred superior parent trees of teak were selected from several plantations in East and Central Java, Indonesia. Of these trees, 65 clones were chosen for the study. The study plantation was established in February 1999 at four different locations (Cepu, Ngawi, Bojonegoro, and Ciamis) in the island of Java, Indonesia (Na'iem 2000). According to the best growth performance of the trees, the same 15 clone trees planted at two different sites, Cepu (7°01' S – 111°32' E) and Ciamis (7°19'S – 108°32'E) were used in the present study (Fig. 2.1). Environmental conditions at the two clonal test sites are shown in Table 2.1. The distance between two sites is approximately 600 km. Although latitudes of two sites are almost the same, precipitation in Ciamis (2740 mm/year) is about two times higher than that in Cepu (1436 mm/year). In addition, dry season in Cepu is longer than in Ciamis (Sumarna 2011). Therefore, these two sites were selected for the present study. Trees were initially planted with 3 × 3-m spacing. After planting, fertilization was not applied, whereas 50% thinning was performed in 2007.

In July 2011, *D*, TH, *V*, SWV, and *P* were measured for total 90 trees of 12-year-old trees from the 15 clones at the two sites with triplicates for each clone. *D* was measured at 1.3 m above the ground using calipers (Haglöf, Sweden). TH was measured using a Haga altimeter (Haga, Germany), and *V* was calculated using the equation proposed by Monteuuis *et al*. (2011).

2.2.2 Stress-wave velocity

The SWV of the stem was measured using a commercial, hand-held stress-wave timer (FAKOPP Microsecond Timer, FAKOPP Enterprise, Hungary) (Ishiguri *et al*. 2007; Fig. 2.2). Start and stop sensors were set at 150 cm and 50 cm from ground level, respectively. The start sensor was hit with a small hammer to create the stress wave. After the stop sensor received the stress wave, the stress-wave propagation time between the two sensors was recorded. Eleven measurements of stress-wave propagation time were obtained for each tree, and the mean value was calculated for each tree. SWV was calculated by dividing the distance between sensors (100 cm) by the averaged stress-wave propagation time.

2.2.3 Pilodyn penetration

The *P* was measured using a Pilodyn tester (strength of spring, 6 J; diameter of pin, 2.5 cm, Proceq, Switzerland) according to the previously reported method (Ishiguri *et al*. 2008; Fig. 2.2). *P* was measured at 1.3 m above ground at three positions for each tree, without removing the bark, and the mean value of *P* was calculated for each tree.

2.2.4 Statistical analysis

Analysis of variance (ANOVA) was applied to examine the differences among clones and the interactions between genotype and environment for growth characteristics, SWV, and *P*. The following model of ANOVA was used for each growth characteristic, SWV, and *P* at each site:

$$Y_{ij} = \mu + S_i + C_j + \varepsilon_{ij}$$

where Y_{ij}, parameter of the *j*-th clone in i-th replication; μ, overall mean; S_i, site effect at the $_i$-th replication; C_j, genetic effect of the *j*-th clone; ε_{ij}, error with Y_{ij}. Repeatabilities of growth characteristics, SWV, and *P* at each site were estimated using the following formula proposed by Falconer (1989) to assess the magnitude of genetic effects:

$$R = \sigma^2_{\mathrm{c}} / [\sigma^2_{\mathrm{c}} + \sigma^2_{\mathrm{e}}]$$

where *R*, repeatability; σ^2_{c}, variance component for clone; σ^2_{e}, variance component of environmental factor. In addition, mean values of the measured properties were also compared between the two sites by paired *t*-test. Furthermore, to asses the interactions between genotype and environment, the following model of ANOVA was used for each growth characteristic, SWV, and *P*:

$$Y_{ijk} = \mu + S_i + C_j + (SC)_{ij} + \varepsilon_{ijk}$$

where Y_{ijk}, parameter of the *k*-th tree of the *j*-th clone in the i-th site; μ, overall mean; S_i, environmental effect of *i*-th site; C_j, genetic effect of *j*-th clone, $(SC)_{ij}$, interaction between *j*-th clone and i-th site; ε_{ijk}, random error.

2.3 Results and discussion

2.3.1 Among clone variations

The mean values for *D*, TH, *V*, SWV, and *P* of the 15 teak clones planted in Cepu were 11.3 – 25.2 cm, 7.7 – 15.7 m, 0.136 – 0.658 m^3, 3.37 – 3.78 km/s, and 18.7 – 27.6 mm, respectively (Table 2.2). The mean values of these characteristics of teak clones planted in Ciamis were 17.0 – 37.7 cm, 12.3 – 23.7 m, 0.295 – 1.472 m^3, 3.23 – 3.77 km/s, and 21.0 – 26.9 mm, respectively (Table 2.3). Monteuuis *et al.* (2011) reported that significant differences in growth characteristics (mortality rate, *D*, TH, *V*, and fork height) were observed among teak trees originating from 42 different genetic sources comprising 26 open-pollinated families from seedlings planted in Malaysia. In addition, the dynamic Young's modulus of elasticity of teak planted in Costa Rica significantly differed among 20 clones (Moya and Marín 2011). In the present study, significant differences were found among the 15 clones for all measured characteristics at both sites (Tables 2.2 and 2.3). The obtained results in this Chapter are consistent with those obtained by previous researchers (Monteuuis *et al.* 2011; Moya and Marín 2011). Therefore, it is considered that, in teak, SWV and *P* are also controlled by genetic factors.

2.3.2 Repeatability

Callister and Collins (2008) reported that H^2 values of *D*, TH, and *V* were 0.37, 0.28, and 0.35, respectively, in 61 clones of 3.5-year-old teak trees. Moya and Marín (2011) reported that the H^2 of the dynamic modulus of elasticity was 0.34 in 10-year-old teak trees planted in Costa Rica. In the present study, *R* of measured characteristics showed relatively moderate to high values (0.27—0.77, Tables 2.2 and 2.3) compared to those obtained by previous researchers (Callister and Collins 2008; Moya and Marín 2011). *R* values in the present study suggest that *D*, TH, *V*, SWV, and *P* are closely related to genetic factors. On the other hand, Monteuuis *et al.* (2011) reported that values for the h^2 of *D*, TH, and *V* in teak gradually increased with tree age. This is also true for other tropical fast-growing clonal tree species, such as *Acacia auriculiformis* (Hai *et al.* 2008). These findings suggest that *R* values are related to tree age. Therefore, *R* of *D*, TH, and *V* obtained in the present study showed relatively higher values than those obtain by other researchers (Callister and Collins 2008; Hai *et al.* 2008). However, further researches are needed to clarify the relationships between the *R* of growth characteristics and tree age.

2.3.3 Effects of environmental factors on growth and other characteristics

Table 2.4 shows the differences in growth characteristics, SWV, and *P* between the two sites. *D*, TH, and *V* differed significantly (1% level) between the two sites.

This is also true for the results of ANOVA test that significant difference in site effect was observed for growth characteristics (Table 2.5). For all growth characteristics, the mean values were higher in Ciamis than in Cepu (Table 2.4). Monteuuis *et al*. (2011) examined growth characteristics, such as *D*, TH, and increment of *V*, in teak trees planted in East Malaysia. They found that the wet tropical conditions positively influenced the growth characteristics of teak. In the present study, as shown in Table 2.1, the mean temperature was almost the same in both sites, whereas precipitation was approximately two times higher in Ciamis than in Cepu. The higher level of precipitation in Ciamis may effect on the growth characteristics. On the other hand, Cordero and Kanninen (2003) reported no significant difference in the oven-dry density of wood between the trees growing in different climatic zones in Costa Rica. Furthermore, Moya and Perez (2008) reported that the physical and chemical characteristics of the soil had almost no impact on the wood properties (specific gravity, normal volumetric shrinkage, and heartwood percentage) of teak trees planted in Costa Rica. In the present study, SWV and *P* did not differ significantly between the two sites (Table 2.4). Therefore, these results suggest that SWV and *P* of teak tree are not largely affected by environmental factors.

In the present study, significant interaction between genotype and environment was found in all measured characteristics (Table 2.5). In addition, SWV and *P* showed lower interaction between genotype and environment than growth characteristics. Na'iem (2000) reported that significant interaction between clone and site was found in *D* and TH for 16-month teak trees planted at four sites in Indonesia. On the other hand, Indira and Bhat (1998) reported that no significant interaction between clone and site was found in basic density of 14-year-old teak clone planted at four sites in India. From these results, when teak plantations are established in Indonesia, interaction between genotype and environment in growth characteristics, SWV, and *P* should be considered. However, further study is needed to clarify the interaction between genotype and environment in teak wood properties.

2.3.4 Relationships among characteristics

Table 2.6 shows the correlation coefficients among tested characteristics. Highly positive significant correlations were found among growth characteristics (*D*, TH, and *V*). High correlation coefficients between *D* and TH were also obtained for teak trees by other researchers (Callister and Collins 2008; Monteuuis *et al*. 2011). In addition, Monteuuis *et al*. (2011) reported that *D* and TH were positively correlated with *V*, respectively. These results indicate that growth characteristics are closely related with each other in teak clones. Thus, *D* is one of the suitable criteria in tree breeding programs of teak for selecting plus trees with good diameter and height growth, and high bole volume.

Some researchers reported no correlation or significant but weak negative correlations between growth characteristics and SWV for some hardwood species (Ishiguri *et al*. 2007; 2011; 2012; Makino *et al*. 2012). In the present study, no significant correlation was observed between growth characteristics and SWV on both sites (Table 2.6), suggesting that SWV of teak is independent of growth characteristics. Thus, mechanical properties are also important criteria for selecting the plus trees in tree breeding programs.

In the present study, relatively high significant correlation coefficients were obtained between growth characteristics and *P* in teak trees planted on both sites (Table 2.6). In general, *P* is closely related to the wood density at outer part of stem (Ishiguri *et al*. 2006; Wu *et al*. 2010). Therefore, it is considered that trees with good growth characteristics result in their lower wood density. However, further research is required to clarify the relationship between *D* and *P* in teak tree.

2.4 Summary

Tree improvement programs for teak have mainly focused on breeding of trees with superior growth characteristics. However, improvement in wood quality should be included in breeding programs for high yield and high quality timber. In the present study, growth characteristics [stem diameter (*D*), tree height (TH), and bole volume (*V*)], stress-wave velocity (SWV), and Pilodyn penetration (*P*) were measured for 15 clones of 12-year-old teak trees planted at two different sites in Indonesia to clarify the variations in tree growth characteristics, SWV, and *P* among clones, their *R*, interaction between genotype and environment, and correlations between measured characteristics. Significant differences of all measured characteristics were found among 15 clones on both sites. Their *R* showed relatively moderate to high values in both sites. These results indicate that these characteristics are closely related to genetic factors. Significant interaction between genotype and environment was found in all measured characteristics, suggesting that interaction between genotype and environment should be considered when the teak plantations are established in Indonesia. In addition, SWV showed lower interaction between genotype and environment than growth characteristics. No significant correlation was found between growth characteristics and SWV, suggesting that SWV is independent of growth characteristics of teak trees. Based on these results, it is considered that wood properties and growth characteristics of teak trees can be improved by application of an appropriate tree breeding program.

Table 2.1 Environmental conditions at the two clonal test sites

	Cepu	Ciamis
Province	Central Java	West Java
South latitude	7°01’	7°19’
East longitude	111°32’	108°32’
Altitude (m)	50	300
Precipitation (mm/year)	1436	2740
Mean temperature (°C)	27.5	25.0
Soil type	Vertisol	Inceptisol
Topography	Flat	Flat

Table 2.2 Growth characteristics, SWV, P and their repeatabilities in 45 teak trees from 15 clones planted at Cepu, Indonesia

Clone code	n	D (cm)	TH (m)	V (m^3)	SWV (km/s)	P (mm)
A	3	17.2	13.8	0.318	3.45	22.9
B	3	16.7	13.2	0.295	3.37	22.2
C	3	17.1	14.8	0.298	3.61	20.5
D	3	11.6	7.7	0.139	3.54	20.4
E	3	16.9	13.2	0.296	3.59	21.5
F	3	21.3	14.8	0.474	3.71	24.3
G	3	14.5	13.8	0.214	3.78	21.9
H	3	14.6	12.8	0.223	3.55	21.6
I	3	17.0	13.7	0.305	3.72	21.4
J	3	11.3	10.3	0.136	3.44	20.9
K	3	17.6	15.7	0.330	3.57	23.4
L	3	14.3	12.3	0.212	3.68	18.7
M	3	12.7	9.2	0.172	3.62	19.9
N	3	17.2	14.7	0.304	3.39	23.2
O	3	25.2	15.0	0.658	3.54	27.6
Significance among clones		**	**	**	*	**
σ^2_c		9.59	3.42	0.013	0.008	3.79
σ^2_e		9.69	5.44	0.012	0.019	2.07
R		0.50	0.39	0.51	0.30	0.65

Note: n, number of trees; D, stem diameter; TH, tree height; V, bole volume; SWV, stress-wave velocity; P, Pilodyn penetration; *, significance at the 5% level; **, significance at the 1% level; σ^2_c, variance component of clone; σ^2_e, variance component of environment; R, repeatability.

Table 2.3 Growth characteristics, SWV, P, and their repeatabilities in 45 teak trees from 15 clones planted at Ciamis, Indonesia

Clone code	n	D (cm)	TH (m)	V (m^3)	SWV (km/s)	P (mm)
A	3	20.2	15.7	0.422	3.54	22.3
B	3	17.6	14.2	0.316	3.48	21.9
C	3	21.5	19.0	0.476	3.56	21.8
D	3	24.8	16.0	0.634	3.63	23.2
E	3	24.8	19.2	0.633	3.51	22.3
F	3	19.3	15.8	0.387	3.23	21.7
G	3	22.1	16.5	0.504	3.69	23.0
H	3	21.7	17.0	0.481	3.39	22.0
I	3	23.5	17.3	0.573	3.51	22.1
J	3	17.0	12.3	0.298	3.38	22.2
K	3	18.2	16.0	0.340	3.40	22.1
L	3	17.0	16.3	0.295	3.50	21.0
M	3	17.8	15.2	0.324	3.77	22.0
N	3	22.1	14.7	0.505	3.51	22.9
O	3	37.7	23.7	1.472	3.65	26.9
Significance among clones		**	**	**	*	**
σ^2_c		24.36	4.78	0.076	0.01	1.47
σ^2_e		7.85	6.04	0.023	0.03	0.97
R		0.76	0.44	0.77	0.27	0.60

Note: n, number of trees; D, stem diameter; TH, tree height; V, bole volume; SWV, stress-wave velocity; P, Pilodyn penetration; *, significance at the 5% level; **, significance at the 1% level; σ^2_c, variance component of clone; σ^2_e, variance component of environment; R, repeatability.

Table 2.4 Comparison of mean values for growth characteristics, SWV, and *P* between the two clonal test sites

Property	Site				Significance between two sites
	Cepu		Ciamis		
	Mean	SD	Mean	SD	
D (cm)	16.3	3.6	21.7	5.2	**
TH (m)	13.0	2.3	16.6	2.6	**
V (m^3)	0.29	0.13	0.51	0.29	**
SWV (km/s)	3.57	0.12	3.52	0.14	ns
P (mm)	22.0	2.1	22.5	1.3	ns

Note: *D*, stem diameter; TH, tree height; *V*, bole volume; SWV, stress-wave velocity; *P*, Pilodyn penetration; ns, no significance; **, significance at the 1% level.

Table 2.5 Across-site analysis of variance in growth characteristics, SWV, and *P*

Source of variation	Degree of freedom	Mean square				
		D	TH	*V*	SWV	*P*
Site	1	638.40**	291.60**	1.08**	0.07 ns	4.70 ns
Clone	14	93.64**	24.96**	0.23**	0.06**	15.60**
Site × Clone	14	25.74**	11.12*	0.07**	0.04*	3.21*
Error	60	8.77	5.74	0.02	0.02	1.52

Note: *D*, stem diameter; TH, tree height; *V*, bole volume; SWV, stress-wave velocity; *P*, Pilodyn penetration; ns, no significance; *, significance at the 5% level; **, significance at the 1% level.

Table 2.6 Correlation coefficients between growth characteristics, SWV, and *P* from15 clones of teak trees at the two test sites

Properties	*D*	TH	*V*	SWV	*P*
D		0.76**	0.99**	0.04ns	0.86**
TH	0.85**		0.68**	0.09ns	0.60**
V	0.99**	0.85**		0.03ns	0.89**
SWV	0.34ns	0.29ns	0.33ns		-0.18ns
P	0.91**	0.66**	0.94**	0.39ns	

Note: Values in lower side of diagonal and upper side of diagonal show correlation coefficients in Cepu and Ciamis, respectively. Used data, mean values from 15 clones; *D*, stem diameter; TH, tree height; *V*, bole volume; SWV, stress-wave velocity; *P*, Pilodyn penetration; ns, no significance; **, significance at the 1% level.

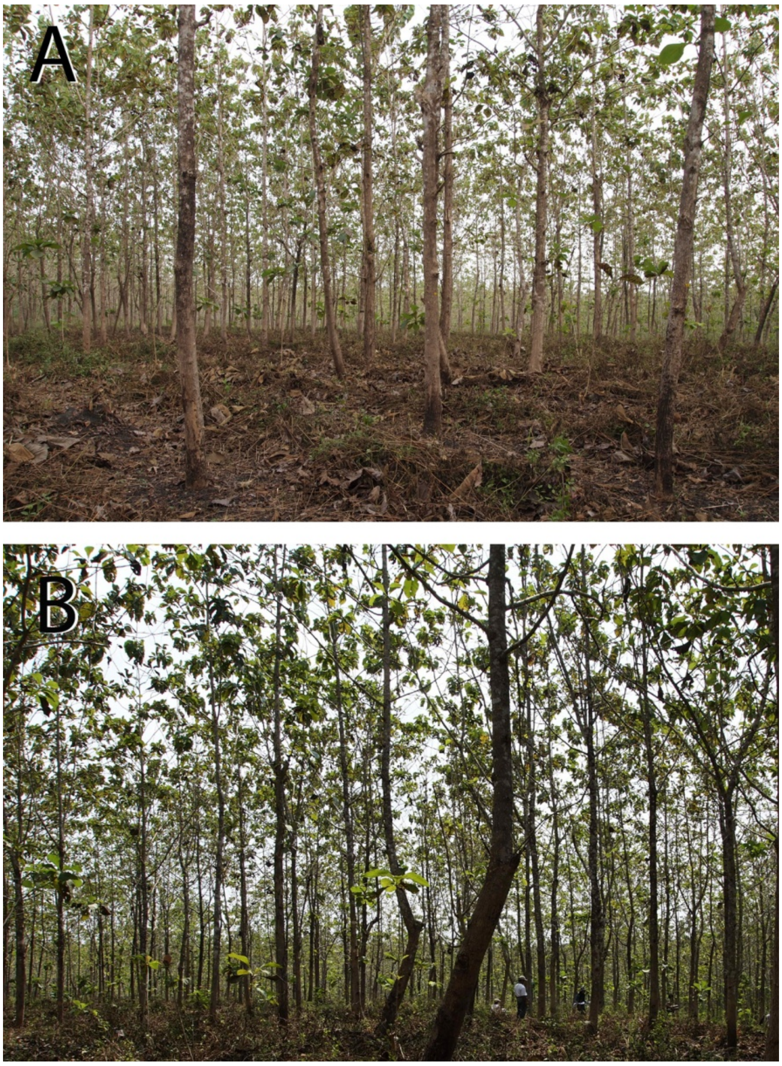


Fig. 2.1 Photographs of teak plantations used in the present study.

Note: Upper (A) and lower (B) photographs show the teak plantations in Cepu and Ciamis, respectively. Both photographs were taken in July, 2011.

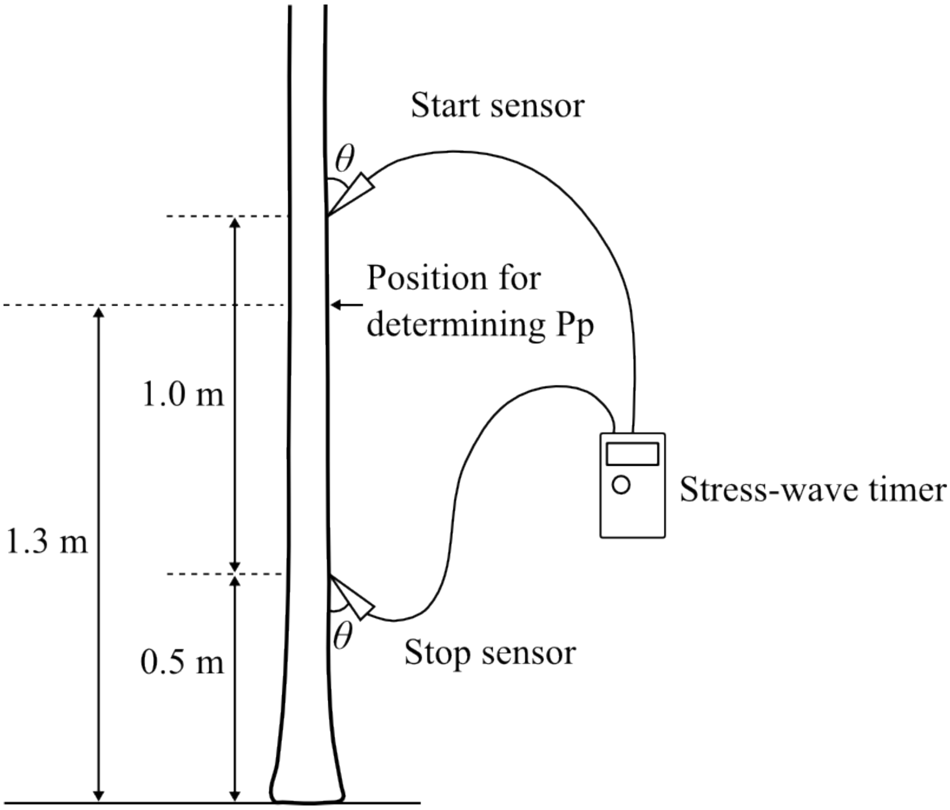


Fig. 2.2 Illustration for measurements of stress-wave velocity and Pilodyn penetration of stem.

Note: Pp, Pilodyn penetration; $\theta = 45°$.

Chapter 3 Variation in tree growth characteristics, stress-wave velocity, and Pilodyn penetration of 24-year-old teak trees originating from 21 seed provenances planted in Indonesia

3.1 Introduction

Provenance trials of growth characteristics in teak trees have been conducted with the purpose of improving the productivity and rotation period of plantations by selecting seeds or sources of cutting. The results have revealed that growth characteristics and stem quality including stem form differ among seed provenances (Chaix *et al*. 2011; Monteuuis *et al*. 2011). However, these studies did not include wood quality traits.

In Chapter 2, growth characteristics, SWV, and *P* were significantly different among 15 clones planted at two different sites in Indonesia. Based on these results, it was concluded that the wood properties of teak trees can be improved by implementing appropriate tree breeding programs.

In Indonesia, seedlings for establishing the commercial teak plantations are mostly obtained by sexual propagation. In general, seed sources in seed production areas have been selected from the plantations based on growth characteristics and stem quality form. The collected seeds are used for establishing commercial teak plantation in Java, Indonesia. Therefore, it is desirable to genetically improve seed quality to establish more productive teak plantations producing good quality wood in Indonesia.

In this Chapter, to characterize genetic variations in growth characteristics and wood properties in the teak trees, tree growth characteristics (*D*, TH, and *V*), SWV, and *P* were investigated for the trees originating from 21 seed provenances planted in Indonesia.

3.2 Materials and methods

3.2.1 Materials

The experimental site of this study was located in the Education Forest of Wanagama, Gadjah Mada University, Yogyakarta, Indonesia (07°54'S – 110°32'E, Fig. 3.1). The provenance trial site for teak was established in February 1988. The environmental conditions of the provenance trial site were as follows: average temperature, 27.7°C; annual precipitation, 1954 mm/year; relative humidity, 80 – 85%; altitude, 214 m above sea level; soil, Mediterranean; topography, flat. Seeds were collected from 21 different provenances in Indonesia and foreign countries (Table 3.1). The seedlings were initially planted at 3 × 3 m spacing. No fertilization or thinning treatments were applied. A total of 155 of 24-year-old trees were used.

D was measured at 1.3 m above the ground using diameter tape (F10-02DM, KDS, Japan). TH was measured using an altimeter (Vertex IV, Haglöf, Sweden), and V was calculated from the equation of Monteuuis *et al*. (2011).

3.2.2 Stress-wave velocity

The SWV was measured by the same method described in 2.2.2.

3.2.3 Pilodyn penetration

The *P* was measured by the same method described in 2.2.3. However, in the present study, the bark at the measuring position was removed before measuring *P*.

3.2.4 Statistical analysis

Analysis of variance (ANOVA) was performed to evaluate the differences in growth characteristics, SWV, and *P* among seed provenances. The ANOVA model was used by the same one described in 2.2.4.

Principal component analysis (PCA) was performed using R software (www.r-project.org) to select seed provenances with good performance for both growth characteristics and wood properties.

3.3 Results and discussion

3.3.1 Among seed provenance variations

The mean values of *D*, TH, *V*, SWV, and *P* in each seed provenance were 14.8 – 31.5 cm, 12.8 – 21.8 m, 0.228 – 1.126 m^3, 3.02 – 3.39 km/s, and 20.4 – 25.9 mm, respectively (Table 3.1).

Table 3.2 shows the result of ANOVA and *R* of the teak trees from 21 seed provenances. Danarto and Hardiyanto (2000) reported that 142 teak families originating in Java and East Nusa Tenggara, Indonesia and planted in East Java showed significant differences in *D*. Chaix *et al*. (2011) reported that *D*, TH, and mortality rate demonstrated significant differences among 41 different seed origins planted in Taliwas, Malaysia. Significant differences in growth characteristics (*D*, TH, *V*, mortality rate, and fork height) were also obtained among teak trees originating from 42 different genetic sources comprising 26 open-pollinated families from the seedlings planted in Sabah, Malaysia (Monteuuis *et al*. 2011). In addition, as described in Chapter 2, significant differences in *D*, TH, and *V* were found among 15 clones of teak trees planted at two different sites in Indonesia (Tables 2.1 and 2.3). The dynamic Young's modulus of teak trees planted in Costa Rica significantly differed among 20 clones (Moya and Marín 2011). Furthermore, SWV and *P* significantly differed among 15 clones of teak trees planted in Indonesia (Tables 2.2 and 2.3). In the present study, the results for growth characteristics, SWV, and *P* obtained from the trees originating in 21 different seed provenances were consistent with those obtained in the previous studies. Therefore, it is considered that growth characteristics, SWV, and *P* are genetically controlled in teak.

3.3.2 Repeatability

Danarto and Hardiyanto (2000) reported the heritability of 0.23 for *D* in 142 families of 12-year-old teak trees planted in East Java, Indonesia. Monteuuis *et al*. (2011) reported h^2 of 0.24, 0.51, and 0.34 for *D*, TH, and *V*, respectively, in 8.8-year-old trees from 42 different genetic sources comprising 26 open-pollinated families from the seedlings planted in Sabah, Malaysia. In addition, the h^2 of *D*, TH, and *V* in 3.5-year-old teak trees from 61 different families planted in Australia were 0.31, 0.22, and 0.29, respectively (Callister and Collins 2008). Chaix *et al*. (2011) reported h^2 of 0.46 and 0.76 for *D* and TH, respectively, in 8.7-year-old teak trees from 26 clonal seed orchard families planted in Taliwas, Malaysia. As described in Chapter 2, the *R* of *D*, TH, *V*, SWV, and *P* in 15 clones of 12-year-old teak trees planted at two different sites in Indonesia were 0.50 and 0.76, 0.39 and 0.44, 0.51 and 0.77, 0.30 and 0.27, and 0.60 and 0.65, respectively (Tables 2.2 and 2.3). Moya and Marín (2011) reported the H^2 of the dynamic modulus was 0.34 in 10-year-old teak trees planted in Costa Rica. Moderate values for the *R* of the measured characteristics in the present study (Table 3.2) indicate the potentials for improving growth characteristics and wood properties in teak with the help of breeding programs.

3.3.3 Relationships among characteristics

Highly positive significant correlations were observed among *D*, TH, and *V* in the present study (Table 3.3). Highly positive correlation coefficients of *D* and TH were also previously reported for teak trees (Callister and Collins 2008; Chaix *et al.* 2011; Monteuuis *et al.* 2011; Hidayati *et al.* 2013b). In addition, *D* and TH were reported to be positively correlated with *V* (Monteuuis *et al.* 2011; Hidayati *et al.* 2013b). These results indicate that growth characteristics are closely related to one another in teak trees. Furthermore, *D* is the suitable criterion in teak breeding programs for selecting plus trees with high wood yield.

No significant correlations were obtained between growth characteristics and SWV in teak trees (Table 3.3), suggesting that SWV in teak is independent of growth characteristics. There is a significant, positive relationship between the SWV of standing trees and the Young's modulus of logs or lumbers (Wang *et al.* 2001; Ishiguri *et al.* 2007, 2008; Wu *et al.* 2011). Therefore, it is considered that mechanical properties, such as Young's modulus are also important criteria for selecting the plus trees in teak breeding programs. As described in Chapter 2, relatively high positive significant correlations between growth characteristics and *P* were found in teak trees planted at two different sites in Indonesia (Table 2.6). In the present study, a moderately significant positive correlation was observed between *D* and *P* (Table 3.3). It is well known that *P* is negatively correlated with wood density (Raymond and MacDonald 1998; Wu *et al.* 2010, 2011). Therefore, it is considered that the trees with good *D* may have lower wood density. Rao and Shashikala (2005) reported that a negative significant correlation was found between growth rate (*D*) and basic density of Thithimathi clones of teak planted in India. However, further studies are required to clarify the relationship between *D* and *P* in teak tree.

3.3.4 Principal component analysis

Principal component analysis (PCA) is a multivariate technique which analyzes a data table in which observations are described by several inter-correlated quantitative dependent variables. Its goal is to extract the important information from the table, to represent it as a set of new orthogonal variables called principal components (PCs), and to display the pattern of similarity of the observations and of the variables as the points in a map. The correlation between a component and a variable estimates the information that they share. In the PCA framework, this correlation is called a loading value (Abdi and Williams 2010). As shown in Table 3.4, the absolute values of loading values for PC 1 were higher in *D* and TH, while that loading value for PC 2 was higher in SWV, indicating that growth characteristics and SWV contribute to PC 1 and PC 2, respectively. SWV of stems has been reported to be positively correlated with the Young's modulus of wood (Wang *et al.* 2001; Ishiguri *et al.* 2007, 2008; Wu *et al.* 2011). Thus, the Young's modulus contributes to PC 2. On the other hand, the seed provenances were well separated as shown in Fig. 3.2, indicating that PCA is a suitable analysis method for selecting the seed provenances with good performances in both growth characteristics and wood properties. In the present study, as the results of PCA, some seed provenances demonstrated high scores for growth characteristics and Young's modulus, such as those from Indonesia [Bangilan (No. 2), Deling (No. 8), and Randublatung (No. 12)] and India [Malabar (No. 14) and Central Province (No. 15)]. Relatively high absolute value of loading value in PC 2 was observed for *P* (Table 3.4), indicating that *P* also contributes to PC 2. *P* is closely related to the wood density of stem (Raymond and MacDonald 1998; Wu *et al.* 2010, 2011). Thus, seed provenances from Bangilan (No. 2) and Blora (No. 10) demonstrated good values for *D* and TH, high values of SWV which are positively correlated with Young's modulus of wood, and low values for *P* (high basic density).

3.4 Summary

Growth characteristics (*D*, TH and *V*), SWV, and *P* were measured for 21 seed provenances of 24-year-old teak trees planted in Indonesia to characterize variation in tree growth characteristics, SWV, and *P* among seed provenances. Repeatability and correlations between the measured characteristics were also determined. Significant differences for all measured characteristics were observed among provenances, indicating that these characteristics are genetically controlled. Repeatabilities of growth characteristics, SWV, and *P* were moderate values. These results indicate the potentials for improving growth characteristics and wood properties of teak trees with the help of breeding programs. Highly significant positive correlations were observed among the growth characteristics, suggesting that they are closely related. In contrast, no significant correlations were observed between the growth characteristics and SWV, indicating that they are independent. It is concluded that mechanical properties are also important criteria for selecting plus trees in tree breeding programs. Principal component analysis revealed that seed provenances from Indonesia (Bangilan, Deling, and Randublatung) and India (Malabar and Central Province) showed high scores of both growth characteristics and SWV, suggesting that they are canditate sources for establishing teak plantation.

Table 3.1 Mean values of growth characteristics, SWV, and *P* in each seed provenance

Code	Seed provenance	*n*	*D* (cm)	TH (m)	*V* (m^3)	SWV (km/s)	*P* (mm)
1	Cepu, Java, Indonesia	7	26.4	19.7	0.728	3.08	23.0
2	Bangilan, Java, Indonesia	8	25.5	18.2	0.688	3.31	22.5
3	Muna, Southeast Sulawesi, Indonesia	7	21.1	15.8	0.473	3.02	24.1
4	Ngliron, Java, Indonesia	8	19.3	15.5	0.403	3.29	23.8
5	Margasari, Java, Indonesia	9	24.7	16.9	0.692	3.16	24.3
6	Ponorogo, Java, Indonesia	9	25.5	18.3	0.699	3.16	24.4
7	Gundih, Java, Indonesia	9	24.1	18.5	0.619	3.10	23.7
8	Deling, Java, Indonesia	6	28.1	21.3	0.895	3.35	23.0
9	Java, Indonesia	5	19.1	14.7	0.389	3.25	23.0
10	Blora, Java, Indonesia	8	25.0	18.0	0.677	3.32	20.4
11	Pati, Java, Indonesia	3	17.2	15.3	0.316	3.39	22.8
12	Randublatung, Java, Indonesia	7	23.0	18.9	0.561	3.31	23.4
13	Soe, Nusa Tenggara, Indonesia	8	19.9	15.3	0.418	3.31	23.5
14	Malabar, India	8	31.5	21.8	1.126	3.26	23.6
15	Central Province, India	11	26.8	20.7	0.798	3.26	25.0
16	Godovari, India	6	26.9	20.4	0.788	3.20	25.9
17	Thailand	10	15.5	15.5	0.256	3.08	21.3
18	Kay, Vietnam	6	14.8	12.8	0.228	3.31	22.1
19	Kouse, Vietnam	7	19.3	15.2	0.401	3.07	23.2
20	Kouai, Vietnam	4	16.7	13.9	0.291	3.29	21.0
21	Myanmar	9	20.9	18.2	0.484	3.19	23.3

Note: *n*, number of trees; *D*, stem diameter; TH, tree height; *V*, bole volume; SWV, stress-wave velocity; *P*, Pilodyn penetration.

Table 3.2 Results of analysis of variance (ANOVA) and repeatability of measured characteristics

Statistical value	D (cm)	TH (m)	V (m^3)	SWV (km/s)	P (mm)
Mean	22.4	17.4	0.568	3.22	23.2
Standard deviation	4.5	2.6	0.233	0.11	1.3
Significance among provenances	**	**	**	**	**
σ^2_c	15.26	4.67	0.036	0.008	1.22
σ^2_e	40.83	12.63	0.145	0.025	4.05
R	0.27	0.27	0.20	0.24	0.23

Note: D, stem diameter; TH, tree height; V, bole volume; SWV, stress-wave velocity; P, Pilodyn penetration; **, significance at the 1% level; σ^2_c, variance component of seed provenance; σ^2_e, variance component of environment; R, repeatability.

Table 3.3 Correlation coefficients between growth characteristics, SWV, and *P*

Factor 1	Factor 2	Correlation coefficient	
D	TH	0.929	**
	V	0.989	**
	SWV	-0.011	ns
	P	0.454	*
TH	*V*	0.925	**
	SWV	0.002	ns
	P	0.430	ns
V	SWV	0.026	ns
	P	0.426	ns
SWV	*P*	-0.239	ns

Note: *D*, stem diameter; TH, tree height; *V*, bole volume; SWV, stress-wave velocity; *P*, Pilodyn penetration; ns, no significance; *, significance at the 5% level; **, significance at the 1% level. Correlation coefficients were determined using mean values of each provenance.

Table 3.4 Loading values from the principal component analysis of stem diameter, tree height, SWV, and *P*

Characteristics	PC 1	PC 2
D	-0.942	0.202
TH	-0.935	0.219
SWV	0.136	0.927
P	-0.686	-0.391

Note: *D*, stem diameter; TH, tree height; SWV, stress-wave velocity; *P*, Pilodyn penetration; PC, principal component.

Fig. 3.1 A photograph of teak seed provenance trial site in the Education Forest of Wanagama, Gadjah Mada University, Yogyakarta, Indonesia.

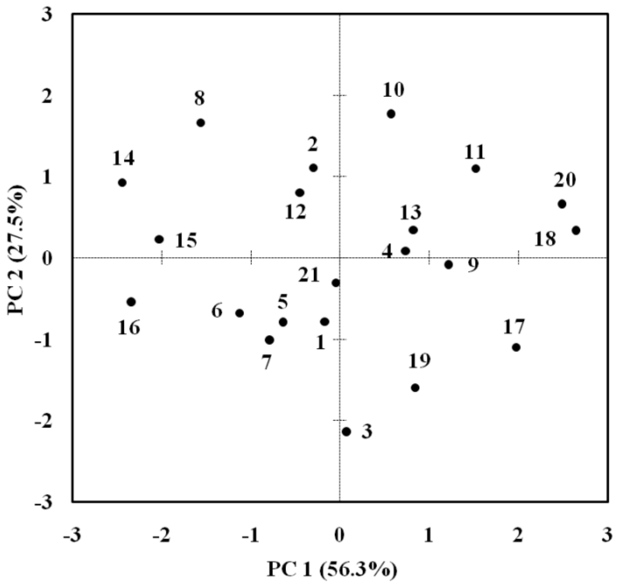


Fig. 3.2 Principal component analysis scores for 21 seed provenances of teak.

Note: Closed circles and numbers indicate the score plots and seed provenances, respectively. PC, principal component.

Chapter 4 Among-clone variations of anatomical characteristics and wood properties in teak planted in Indonesia

4.1 Introduction

In Chapter 2, *D*, TH, *V*, SWV, and *P* were investigated for fifteen 12-year-old teak clones planted at 2 sites. Among-clone differences were found among the 15 clones in all characteristics, whereas the differences between the two sites were found only in growth characteristics (*D*, TH, and *V*). Based on these results, it was concluded that the wood properties of teak trees can be improved by tree breeding programs.

Wood density is affected by several wood structures, including the cell size, cell wall thickness, and some other factors (Zobel and van Buijtenen 1989). Variations in wood structure have significant effects on the wood quality. In general, basic density is an important factor affecting the wood properties (Zobel and van Buijtenen 1989). Compressive strength is also one of the important mechanical properties for solid lumber (Thulasidas and Bhat 2012). However, the information on the anatomical characteristics and wood properties is still limited and required to elucidate their importance for teak breeding programs in Indonesia.

To utilize the faster growing trees, it is important to know whether xylem maturation depends on cambium age or tree diameter, during the maturation process occurs. Understanding the maturation process is crucial not only for forest management, but also for avoiding the problems to manufacturers and consumers (Kojima *et al*. 2009). Xylem maturation of some fast-growing species, such as *A. mangium* and *F. moluccana*, depends on diameter growth (Honjo *et al*. 2005; Kojima *et al*. 2009; Makino *et al*. 2012). In contrast, xylem maturation of *Eucalyptus* spp. and *Shorea acuminatissima* depends on cambial age (Kojim*a et al*. 2009; Ishiguri *et al*. 2012). In teak, Bhat *et al*. (2001) reported that maturation begins approximately at 15 - 25 years of age, depending on the property, growth rate, individuality, and plantation site. However, the mechanism of xylem maturation in teak trees remains unclear.

In this Chapter, anatomical characteristics [vessel diameter (VD), fiber wall thickness (FWT), fiber diameter (FD), vessel element length (VEL), and fiber length (FL)] and wood properties [basic density (BD) and compressive strength parallel to grain (CS) at the green condition] were determined for nine 12-year-old teak clones planted in Java Island, Indonesia. Based on the results, the variation among-clones, *R*, radial variations of the anatomical characteristics and wood properties, and relationships between the properties were discussed.

4.2 Materials and methods

4.2.1 Materials

A total of twenty-seven, 12-year-old teak trees from representing nine clones (clones P-X) with 2-5 replications for each clone were used in the present study (Table 4.1). The clonal test sites were located in Cepu and Ciamis. The environmental conditions of the sites were described in Table 2.1.

For determining the anatomical characteristics and wood properties, core samples (5 mm in diameter) from pith to bark were collected using a borer (Haglöf) at 1.3 m above the ground level (Fig. 4.1). Three core samples were collected from each tree at the circumferential position. Using the core samples, the anatomical characteristics (VD, FWT, FD, VEL, and FL) and wood properties (BD and CS) were determined from pith to bark. It is known that false ring sometimes occurs in teak because of the environmental factors (Priya and Bhat 1998; Palakit *et al*. 2012). Thus, the core samples were cut at 1-cm intervals from pith to bark for determining radial variations of the anatomical characteristics and wood properties. For determining CS, the samples at 5-mm intervals from pith to bark were cut into small pieces.

4.2.2. Anatomical characteristics

Transverse sections (20 μm in thickness) were obtained from each 1-cm segment with a sliding microtome (ROM-380, Yamato, Japan). The sections were stained with safranin, dehydrated, and mounted in bioleit. Digital images of the transverse sections were captured into a personal computer and analyzed with ImageJ software (National Institutes of Health, USA). The tangential and radial diameters were measured for 30 vessels and 50 wood fibers in each 1-cm segment, and then mean values were calculated. The double wall thicknesses of 50 wood fiber cells were measured, and one half of the double wall thickness was defined as FWT. Small strip specimens were macerated with Schulze's solution for measuring VEL and FL. A total of 30 vessel elements and 50 wood fibers were measured using a microprojector (V-12, Nikon, Japan) and a digital caliper (CD-15CP, Mitutoyo, Japan). All anatomical characteristics were measured except for pore and terminal zone at the growth ring.

4.2.3 Wood properties

The green volume of each segment was measured using the water displacement method and the oven-dried weight was determined by drying the segment to a constant weight at 105±3°C in a laboratory oven (WFO-450ND, EYELA, Japan). BD was calculated by dividing the oven-dried weight by the green volume. CS at the green condition was measured using a core sample testing machine (Fractometer II, IML, Germany) by the method described by Matsumoto *et al*. (2010a). A specimen was placed in the testing machine, and then a load was applied in the longitudinal direction. The CS value indicated by the testing machine was recorded for each specimen. The mean value of CS at 1-cm intervals was calculated before analysis of radial variation.

4.2.4 Statistical analysis

Table 4.2 shows the stem diameter, anatomical characteristics, and wood properties of clone Q from the two clonal test sites. In Chapter 2, a significant difference between two sites was recognized only in *D*, a growth characteristics (Table 2.4). Therefore, data from the two different sites were combined to analyze among-clone variation of the anatomical characteristics and wood properties. Analyses of variance (ANOVA) were performed to evaluate the differences in anatomical characteristics and wood properties among clones. The ANOVA model described in 2.2.4 was used .

4.2.5 Evaluation of xylem maturation process

Radial variation of FL with respect to relative distance from the pith was calculated for evaluating the xylem maturation process. Figure 4.2 shows the calculation method for converting measured FL into the value in the relative distance from the pith (Chowdhury *et al*. 2009b). A total of 10 trees at the same age with different radial growth rates (five trees with faster growth and five trees with slower growth) were selected.

4.3 Results and discussion

4.3.1 Anatomical characteristics

The highest values of VD, FWT, FD, VEL, and FL were 196 µm, 2.89 µm, 24.5 µm, 0.293 mm, and 1.48 mm for clones W, P, X, Q, and R, respectively. The lowest values of VD, FWT, FD, VEL, and FL were 175 µm, 2.58 µm, 22.8 µm, 0.268 mm, and 1.38 mm for clones P, S, P, P, and S and V, respectively (Table 4.3). In some hardwood species, such as *E. camaldulensis*, acacia hybrid, and *A. mangium*, no significant differences were found in VD, FWT, FD, VEL, and FL among clones and provenances (Veenin *et al*. 2005; Kim *et al*. 2008; Nugroho *et al*. 2012). In contrast, in *Populus deltoides*, significant differences among clones were recognized in VD, FWT, FD, VEL, and FL (Pande 2011; Pande and Dhiman 2011). In the present study, a significant difference was found only in VEL. Table 4.3 shows the results of ANOVA and *R* of the anatomical characteristics for the nine clones. In the present study, moderate values of *R* were obtained for VEL (0.36) and FD (0.22) (Table 4.3), whereas *R* values could not be calculated for the other characteristics.

4.3.2 Wood properties

Table 4.4 shows the mean values of wood properties in the nine clones. The highest values of BD and CS at the green condition were 0.58 g/cm^3 and 42.9 MPa, respectively, for clone P, and the lowest values were 0.48 g/cm^3 and 33.7 MPa, respectively, for clone S. Furthermore, BD and CS were significantly different among clones (Table 4.4). Indira and Bhat (1998) reported a significant difference in BD among eighteen 14-year-old teak clones planted in India. Nocetti *et al*. (2011) found that wood density significantly differed among 13 provenances of teak planted in Ghana. Significant differences in wood density among clones were also found in some hardwood species, such as acacia hybrid and *P. deltoides* (Kim *et al*. 2008; Pande and Dhiman 2011). CS was significantly different between two provenances of teak trees (Bhat and Priya 2004). Furthermore, moderate values of *R* for BD were obtained in other hardwood species, such as *A. auriculiformis* and *P. deltoides* (Hai *et al*. 2010; Pande and Dhiman 2011). However, the studies on *R* or heritability in compressive strength are limited. With respect to other mechanical properties, Moya and Marín (2011) reported that the H^2 of the dynamic modulus of elasticity was 0.34 in 10-year-old teak trees planted in Costa Rica. In the present study, significant differences were found among clones, and R of BD and CS showed moderate to high values (Table 4.4), indicating that BD and CS are genetically controlled in teak. It is, therefore, considered that BD and CS are critical properties for improving the wood quality in teak tree breeding programs.

4.3.3 Relationships between properties

Table 4.5 shows the correlation coefficients between the measured characteristics. A significant correlation between the anatomical characteristics was found only between VD and VEL. On the other hand, some significant correlations were found between the anatomical characteristics and wood properties. Furthermore, a significant positive correlation was found between BD and FWT (Table 4.5). In 35-year-old teak trees planted in India, air-dry density was positively and significantly correlated with double wall thickness, and CS was also correlated with air-dry density and double wall thickness (Thulasidas and Bhat 2012). Similar results have been reported for other hardwood species (Ishiguri *et al.* 2009; Chowdhury *et al.* 2009a,b, 2012; Matsumoto *et al.* 2010a; Makino *et al.* 2012). These results indicate that FWT is strongly correlated with BD in teak.

4.3.4 Radial variations of measured characteristics

Radial variations of VD and FWT gradually increased from pith to bark (Fig. 4.3). FD slightly increased near the pith and then became almost constant outward (Fig. 4.3). Bhat *et al.* (2001) reported that VD increased during the juvenile phase and then stabilized at approximately 20 year. In other hardwood species with long rotations, FWT increased from pith to bark, whereas FD was almost constant from pith to bark in *S. acuminatissima* (Ishiguri *et al.* 2012). In the present study, radial variations of VD, FWT, and FD (Fig. 4.3) were almost similar to those reported in previous studies (Bhat *et al.* 2001; Ishiguri *et al.* 2012). Radial variations of VEL and FL showed a gradual increase from pith to bark (Fig. 4.4). In teak trees, it was reported that FL increased up to 15-20 years and then became constant outward (Bhat *et al.* 2001). They also reported that the mean values of FL in juvenile and mature woods from fast-growing trees were 1.28 and 1.50 mm, respectively, while

FL in juvenile and mature woods of slow-growing trees were 1.10 and 1.38 mm, respectively (Bhat *et al.* 2001). Furthermore, in the present study, radial variation of BD also showed a gradual increase from pith to bark (Fig. 4.5). In contrast, Bhat *et al.* (2001) reported that BD varied relatively little from pith to bark. They also reported that CS varied little and slightly increased from pith up to 20 cm (the juvenile-wood area). In the present study, radial variation of CS agreed with that reported in a previous study (Bhat *et al.* 2001). Thus, the trends of radial variations of the anatomical characteristics and wood properties were similar for all clones in this study.

Radial variation of FL determined by the relative distance from the pith was also examined. Figure 4.6 shows radial variation of FL in the ten selected trees (five with faster radial growth rate and five with slower radial growth rate). The radial profile in relation to relative distance from the pith showed almost the same pattern for the two radial growth rate categories (Fig. 4.6), suggesting that xylem maturation in teak tree depends on cambial age rather than stem diameter growth. It has been reported that xylem maturation in some fast-growing species, such as *A. mangium* and *F. moluccana,* depends on diameter growth (Honjo *et al.* 2005; Kojima *et al.* 2009; Makino *et al.* 2012). In contrast, xylem maturation in *Eucalyptus* spp. and *S. acuminatissima* was reported to depend on cambial age (Kojima *et al.* 2009; Ishiguri *et al.* 2012). Bhat *et al.* (2001) reported that the maturity of teak begins approximately at 15-25 year. Although the tree age used in the present study was relatively younger, the results of this study, suggest that xylem maturation in teak depends on cambial age, being consistent with those obtained by Bhat *et al.* (2001). It is, therefore, concluded that after formation of mature wood, intensive silvicultural practices should be applied to produce as much mature wood as possible in teak tree.

4.4 Summary

The anatomical characteristics and wood properties were investigated for 27 trees from 9 teak clones planted in Indonesia. Clone P showed the lowest values of VD, FD, and VEL and the highest values of FWT, BD, and CS. The mean values of VD, FWT, FD, VEL, FL, BD, and CS were 188 μm, 2.78 μm, 23.4 μm, 0.284 mm, 1.42 mm, 0.51 g/cm^3, and 37.5 MPa, respectively. Significant differences among the nine clones were found in VEL, BD, and CS. Moderate to high values of *R* were obtained for FD, VEL, BD, and CS, indicating that these characteristics are genetically controlled. Radial variation of FL with respect to relative distance from the pith showed almost the same pattern for the two radial-growth-rate categories, suggesting that xylem maturation depends on cambial age rather than stem diameter growth in teak tree. It is, therefore, concluded that after forming the mature wood, intensive silvicultural practices should be applied to produce as much mature wood as possible in teak tree.

Table 4.1 Statistical values of stem diameter and tree height of sample trees

Clone code	Site	*n*	*D* (cm)		TH (m)	
			Mean	SD	Mean	SD
P	Ciamis	2	21.3	3.6	17.0	0.0
Q	Cepu	3	17.1	1.0	14.8	1.9
Q	Ciamis	2	23.1	0.4	18.0	1.4
R	Ciamis	3	23.2	2.0	15.7	2.1
S	Ciamis	3	19.6	2.4	14.8	4.1
T	Ciamis	3	21.7	1.0	17.0	3.3
U	Cepu	3	17.6	1.6	12.0	3.6
V	Cepu	2	17.1	2.0	12.8	3.2
W	Cepu	3	17.2	1.0	14.7	0.8
X	Cepu	3	17.3	1.8	14.0	2.6
Mean/total		27	19.5	2.6	15.1	1.9

Note: *n*, number of trees; SD, standard deviation; *D*, stem diameter; TH, tree height.

Table 4.2 Comparison of mean values of anatomical characteristics and wood properties of clone Q between the 2 clonal test sites

Character	Cepu (n = 3)		Ciamis (n = 2)		Significant between two sites
	Mean	SD	Mean	SD	
D (cm)	17.1	1.0	23.1	0.4	**
VD (μm)	182	10	196	0.3	ns
FWT (μm)	2.78	0.14	2.92	0.01	ns
FD (μm)	23.3	1.4	23.3	0.9	ns
VEL (mm)	0.289	0.002	0.300	0.006	ns
FL (mm)	1.41	0.1	1.52	0.01	ns
BD (g/cm^3)	0.51	0.03	0.52	0.02	ns
CS (MPa)	39.1	2.9	37.9	0.2	ns

Note: n, number of trees; SD, standard deviation; D, stem diameter; VD, vessel diameter; FWT, fiber wall thickness; FD, fiber diameter; VEL, vessel element length; FL, fiber length; BD, basic density; CS, compressive strength parallel to grain; **, significance at 1% level; ns, no significance.

Table 4.3 Statistical values of anatomical characteristics of each clone

Clone code	Number of trees	VD (μm)		FWT (μm)		FD (μm)		VEL (mm)		FL (mm)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
P	2	175	17	2.89	0.16	22.8	0.2	0.268	0.001	1.42	0.09
Q	5	188	10	2.84	0.12	23.3	1.1	0.293	0.007	1.46	0.09
R	3	190	9	2.77	0.15	23.4	0.5	0.290	0.007	1.48	0.02
S	3	189	7	2.58	0.20	23.1	0.2	0.272	0.010	1.38	0.10
T	3	195	10	2.77	0.08	23.8	0.5	0.283	0.013	1.39	0.07
U	3	188	11	2.82	0.17	23.7	0.8	0.284	0.013	1.43	0.05
V	2	188	5	2.85	0.19	23.0	0.6	0.282	0.001	1.38	0.13
W	3	196	14	2.69	0.22	23.1	0.3	0.291	0.010	1.41	0.04
X	3	187	6	2.85	0.27	24.5	0.5	0.289	0.007	1.44	0.04
Mean/total	27	188	6	2.78	0.10	23.4	0.5	0.284	0.009	1.42	0.04
Significance among clones		ns		ns		ns		*		ns	
σ^2_c		-		-		0.125		0.000047		-	
σ^2_e		104.0		0.031		0.452		0.000084		0.005	
R^2		-		-		0.22		0.36		-	

Note: SD, standard deviation; VD, vessel diameter; FWT, fiber wall thickness; FD, fiber diameter; VEL, vessel element length; FL, fiber length; *, significance at 5% level; ns, no significance; σ^2_c, variance component of clone; σ^2_e, variance component of environment; R^2, repeatability.

Table 4.4 Statistical values of wood properties in each clone

Clone code	*n*	BD (g/cm^3)		CS (MPa)	
		Mean	SD	Mean	SD
P	2	0.58	0.02	42.9	0.0
Q	5	0.51	0.02	38.6	2.2
R	3	0.50	0.03	35.7	3.0
S	3	0.48	0.03	33.7	0.3
T	3	0.51	0.03	34.6	2.6
U	3	0.51	0.03	39.9	1.3
V	2	0.53	0.01	39.2	1.3
W	3	0.49	0.03	34.0	1.8
X	3	0.52	0.00	38.6	1.4
Mean/total	27	0.51	0.03	37.5	3.1
Significance among clones		*		**	
σ^2_c		0.0004		6.881	
σ^2_e		0.0007		4.510	
R		0.39		0.60	

Note: *n*, number of trees; SD, standard deviation; BD, basic density; CS, compressive strength parallel to grain at green condition; **, significance at 1% level; *, significance at 5% level; σ^2_c, variance component of clone; σ^2_e, variance component of environment; *R*, repeatability.

Table 4.5 Correlation coefficients between measured characteristics

Factor 1	Factor 2	Correlation coefficient	
VD	FWT	-0.071	ns
	FD	0.276	ns
	VEL	0.436	*
	FL	0.172	ns
	BD	-0.353	ns
	CS	-0.540	**
FWT	FD	0.035	ns
	VEL	-0.041	ns
	FL	0.344	ns
	BD	0.535	**
	CS	0.574	**
FD	VEL	0.342	ns
	FL	-0.001	ns
	BD	0.139	ns
	CS	-0.054	ns
VEL	FL	0.283	ns
	BD	-0.362	ns
	CS	-0.164	ns
FL	BD	0.177	ns
	CS	0.122	ns
BD	CS	0.719	**

Note: VD, vessel diameter; FWT, fiber wall thickness; FD, fiber diameter; VEL, vessel element length; FL, fiber length; BD, basic density; CS, compressive strength parallel to grain; **, significance at 1% level; *, significance at 5% level; ns, no significance.

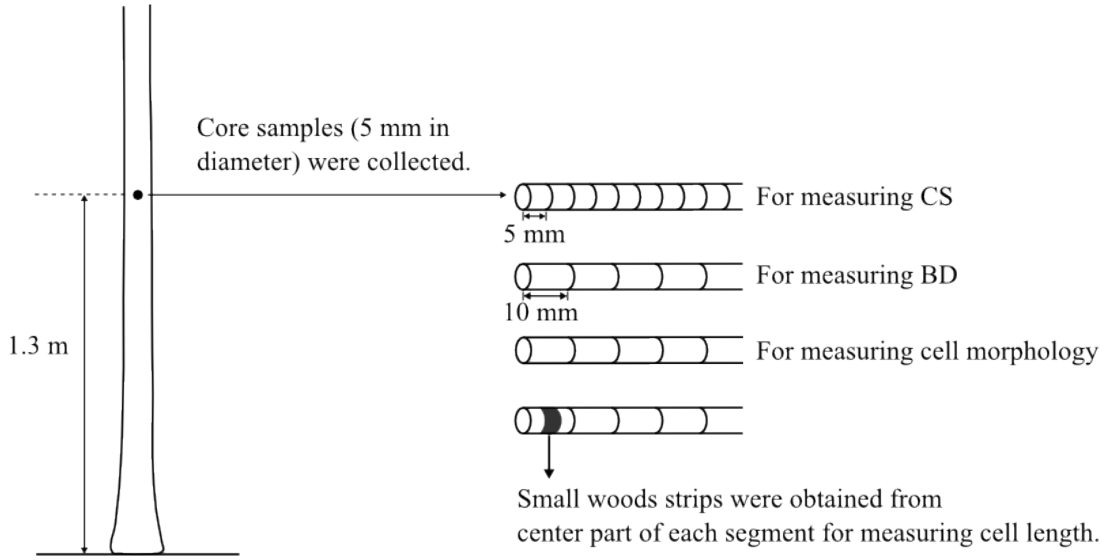
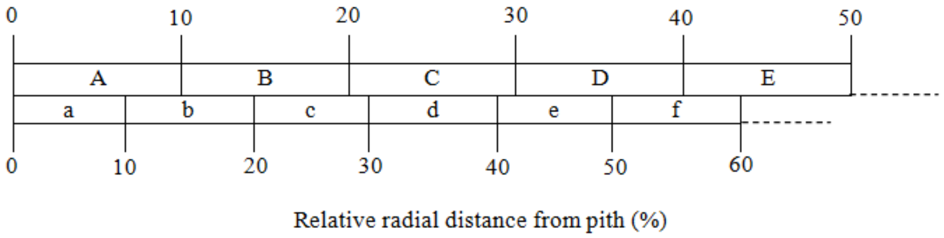


Fig. 4.1 Illustration of sampling and experiment procedures in this Chapter.

Note: CS, compressive strength; BD, basic density.



For example: radial distance (d) = 70 mm

Distance at 10% relative radial distance = d /10 = 7 mm

$a = 7A / 7$
$b = (3A + 4B) / 7$
$c = (6B + 1C) / 7$
$d = 7C / 7$
$e = (2C + 5D) / 7$
$f = (5D + 2E) / 7$

Fig. 4.2 Method for calculating of wood properties with respect to relative distance from the pith (Chowdury *et al*. 2009b).

Note: Capital and small letters indicate the measured value of fiber length and calculated value of fiber length, respectively.

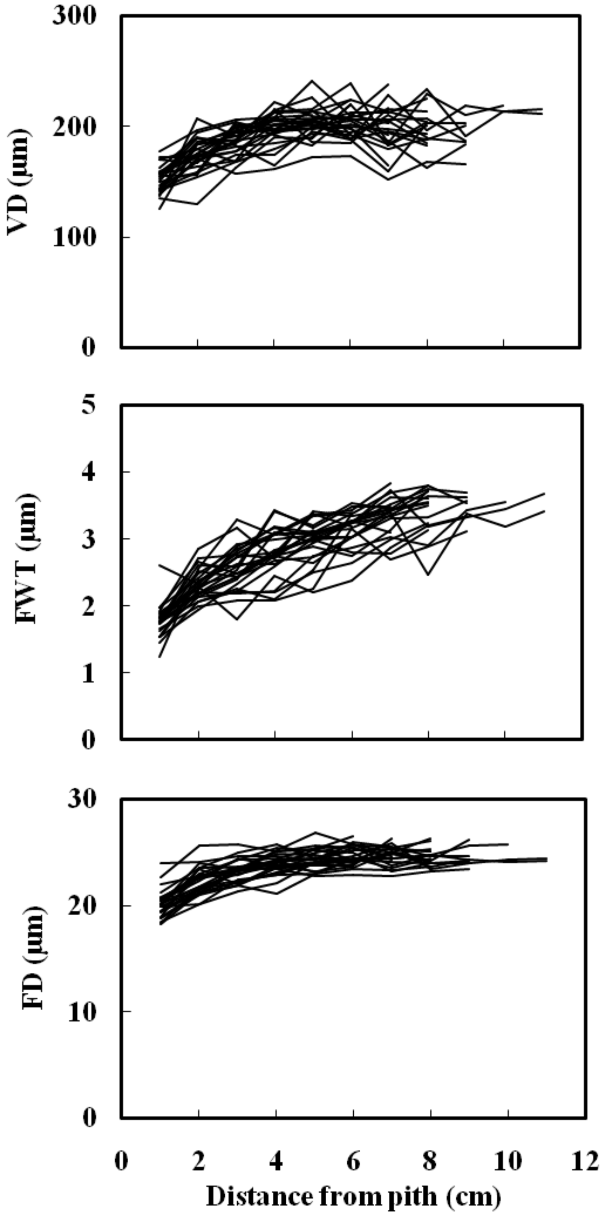


Fig. 4.3 Radial variations of VD, FWT, and FD from pith to bark in 27 trees from nine clones.

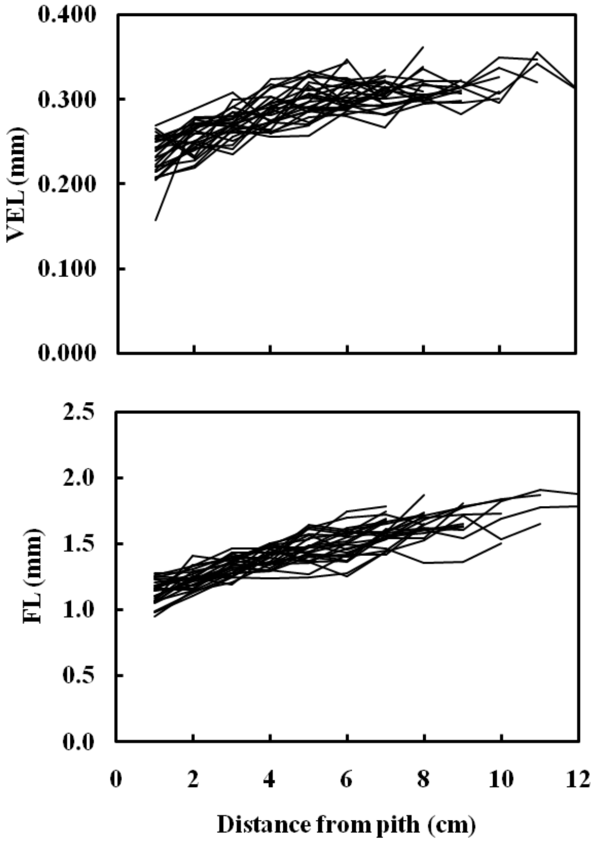


Fig. 4.4 Radial variations of VEL and FL from pith to bark in 27 trees from nine clones.

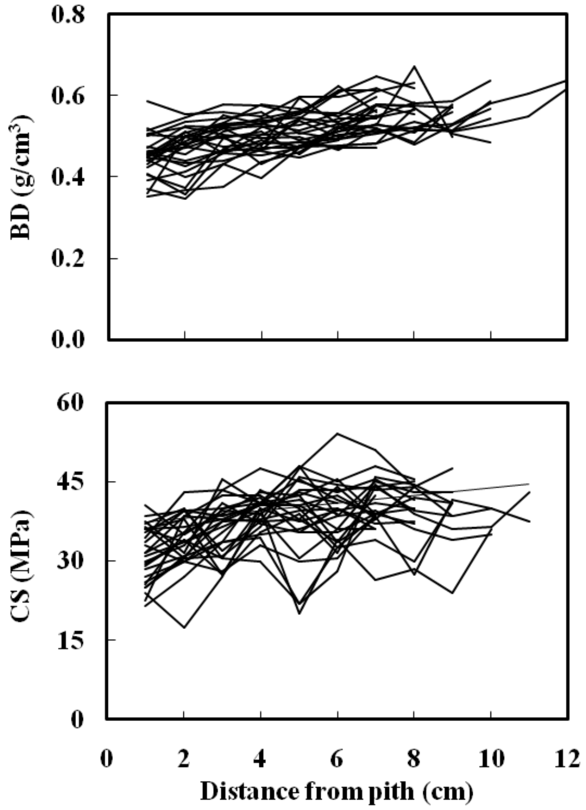


Fig. 4.5 Radial variations of BD and CS at the green condition from pith to bark in 27 trees from nine clones.

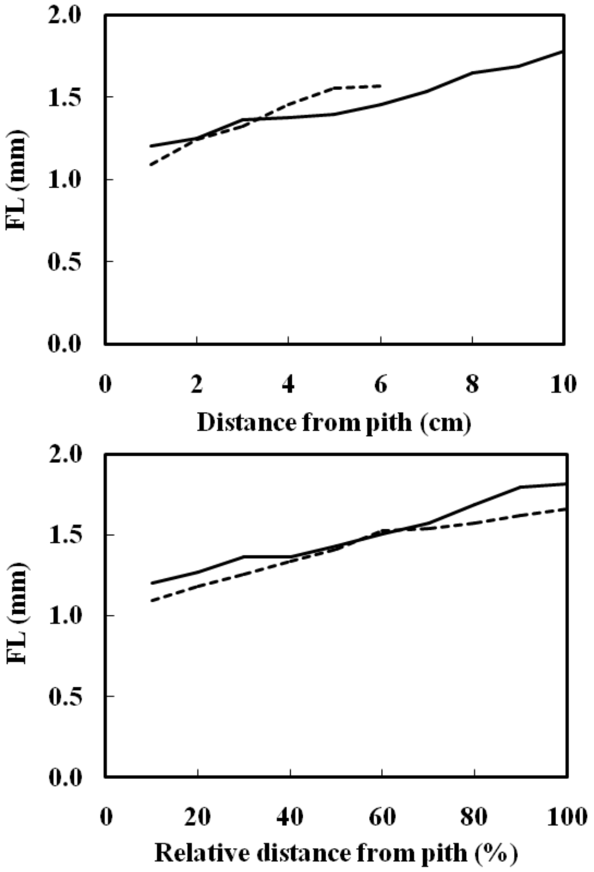


Fig. 4.6 Radial variations of FL with respect to distance from the pith and relative distance from the pith in the ten selected trees with different radial growth rates.

Note: Solid line indicates the mean value of five trees with faster radial growth rate; dotted line indicates the mean value of five trees with slower radial growth rate.

Chapter 5 Variation of decay resistance, heartwood color, and extractive contents in 12-year-old teak clones planted in Indonesia

5.1 Introduction

Durability of wood depends on several factors, including genetic origin of tree, silviculture, climate, and local environment (Kokutse *et al*. 2006). Heritability of decay resistance has been estimated from low to high values in *Eucalyptus* spp. (Poke *et al*. 2006; Bush *et al*. 2011). On the other hand, extractive contents can also provide trees with resistance to disease and insect attack (Hillis 1987). Extractive content are usually strongly inherited, while there are a few studies showing the low inheritance value (Zobel and Jett 1995).

It is known that teak wood has natural durability against fungal and insect attacks (Rudman *et al*. 1967; Yamamoto and Hong 1989; Thulasidas and Bhat 2007; Lukmandaru and Takahasi 2008, 2009). The high natural durability of teak wood is attributed by existence of various extractives, such as anthraquinones, tectoquinones, and others which have been considered as bioactive compounds (Soerianegara and Lemmens 1994; Yamamoto *et al*. 1998; Lukmandaru and Takahashi 2008). Haupt *et al*. (2003) identified tectoquinone as a bioactive compound for the inhibition of *Trametes versicolor* (Syn. *Coriolus versicolor*). In addition, Niamké *et al*. (2011) reported that tectoquinone and 2-(hydroxymethyl)anthraquinone isolated from teak wood had strong correlations with mass loss of wood attacked by *Antrodia* sp. On the other hand, Kokutse *et al*. (2006) pointed out that the information on the natural durability of teak is important for breeding programs and wood use. However, research on variation of decay resistance and extractive contents is still limited in teak wood.

Color is one of the quality criteria of wood to asses its suitability for certain end-uses, such as furniture and decorative veneers (Thulasidas *et al*. 2006; Moya and Marín 2011). This is also true for the teak wood: heartwood color of teak wood is an important factor to fix wood price (Thulasidas *et al*. 2006). On the other hand, though wood color is generally thought to be influenced by the environment, reasonably strong genetic component has been found for some species (Zobel and Jett 1995). In addition, many researchers have reported the effects of wood color on other properties, such as mass loss, and the effects of the environmental factors on the wood color (Kokutse *et al.* 2006; Thulasidas *et al.* 2006; Lukmandaru and Takahashi 2008; Moya and Berrocal 2010; Moya and Marín 2011).

In this Chapter, the variations of decay resistance, heartwood color, and extractive contents were clarified for nine clones planted in Indonesia. Furthermore, the relationships between mass loss and other characteristics were also discussed.

5.2 Materials and methods

5.2.1 Materials

The materials used in this Chapter were the same ones used in Chapter 4 (4.2.1). Total 26 trees from nine clones were used. Core samples (5 mm in diameter) from pith to bark were collected using a borer (Haglöf) at 1.3 m above the ground level. Some core samples were also collected from each tree at the circumferential position.

5.2.2 Decay test

Decay test was conducted by the method described by Matsumoto *et al.* (2010b). The increment cores of heartwood were cut into about 3 cm length. Before incubation, 26 specimens were dried for one day at 60°C and then weighed. All of specimens were sterilized with propylene oxide for two days in a desicator in vacuo. A total of 26 specimens were decayed by a white-rot fungus, *Trametes versicolor* 1030. This fungus was provided by the Forestry and Forest Products Research Institute (Tsukuba, Japan). The fungus was precultured on a potato-dextrose-agar (Difco Laboratories, USA) slant medium in a test tube (1.5 cm in diameter and 15 cm in length). After mycelia had spread on the medium, the specimens, of which the moisture content had been adjusted to 50-60% by dipping into sterilized distilled water, were put onto the medium in the test tubes. Then, the specimens with the fungus were incubated at 26°C in the dark. After 60 days of culture, the specimens were collected from the culture medium. The mycelia were carefully removed from the surface of the decayed specimens. Then the specimens were oven-dried for one day at 60°C. The dry weight of the decayed specimens was measured in order to calculate the percentage of weight loss.

5.2.3 Heartwood color

For measuring heartwood color, wood meals of heartwood were prepared from the core samples by using a rotary speed mill (P-14, Fritsch, Germany). Boundary between heartwood and sapwood was confirmed by naked eyes. The obtained wood meals were packed in transparent plastic bags. Color of packed heartwood meal was measured using a colorimeter (CR 200, Minolta, Japan). The CIELAB (L^*, a^*, b^*) system was employed to evaluate the heartwood color. The values of L^*, a^*, and b^* indicate psychometric lightness (0 = black — 100 = white), a color parameter on the red / green axis, and a color parameter on the yellow / blue axis, respectively.

5.2.4 Ethanol-toluene extract contents

After the measurement of heartwood color, ethanol-toluene extract content of heartwood was determined. About 1 – 4 g of the sample was extracted with 120 mL of ethanol-toluene mixture (1 : 2, v : v) using a Soxhlet extractor for 6 h. After extraction, the solvent dissolving the extracts was evaporated off. The flask containing the extractives was air-dried, and then dried in the oven at 105 ± 3°C. The amount of extract content was determined by the oven-dried weight.

5.2.5 Quantification of extractives

It has been reported that teak wood contains various types of extractives (Windeisen *et al*. 2003; Lukmandaru *et al*. 2009; Lukmandaru and Takahashi 2009, Niamké *et al*. 2011). In the present study, the contents of six extractives, tectoquinone, palmitic acid, lapachol, 2-(hydroxymethyl)anthraquinone, and squalene, were determined.

The ethanol-toluene extracts prepared by the method described in 5.2.4 were dissolved in *n*-hexane and methanol seperately. The both solutions were combained and moved into small sample bottles, and then the bottles were kept in a fume hood until the solvents were evaporated off. After drying, the bottles containing the extracts were stored in a freezer (-20°C) just before use. For quantification, the following compounds, were used as standards; tectoquinone (2-methylanthraquinone, Kanto Chemical, Japan), palmitic acid (Kanto Chemical, Japan), lapachol (Sigma-Aldrich, USA), 2-(hydroxymethyl)anthraquinone (Sigma-Aldrich, USA), and squalene (Kanto Chemical, Japan).

One mg of the extract samples or standards except for squalene was dissolved in 1 mL of pyridine (Wako Chemical, Japan). In the case of squalene, 1 μL of squalene was dissolved in 1 mL of pryrine. After that, 1 μL of 3,4,5-trimetoxyphenol solution as an internal standard was mixed with the 100 μL of the extract solution. Furthermore, 150 μL of *N*,*O*–bis(trimethylsilyl)trifluoroacetamide (BSTFA) was added to each solution, and then the solution was heated at 75°C by oil bath for 30 min.

The extractives were identified by comparing their mass spectra and retention time with those of standards using a gas chromatograph-mass spectrometer (GC-MS, Focus GC DSQ II, Thermo, USA). GC-MS conditions were as follow: detector: electron impact ionization (EI) with ionization voltage at 70 eV, column: DB-1 (15 m x 0.25 mm (i.d.), film thickness 0.25 μm, Agilent J&W, USA), ion source temperature: 300°C. The other conditions were the same with GC analysis.

The extractive contents were determined by a gas chromatograph (GC, HP 6890 series, Agilent, USA) under the following conditions: detector: FID, column: DB-1 capillary column (30 m x 0.25 mm (i.d.), film thickness 0.25 μm, Agilent J&W, USA), inlet temperature: 300°C, inlet flow: 1.5 mL/min, injection mode: split 10:1, column temperature: 100 – 300°C (5°C/min), detector temperature: 300°C, carrier gas: helium, carrier gas flow 0.8 mL/min. One μL of the sample solution was injected manually into the GC. The retention time of the standards for the five extractives quantified in the present study were as follows: tectoquinone, 26.819 min; palmitic acid, 26.762 min; lapachol, 27.736 min; 2-(hydroxymethyl)anthraquinone 33.210 min; squalene, 38.830 min.

5.2.6 Statistical analysis

In Chapters 2 and 4, significant differences among sites were recognized only in growth characteristics (Tables 2.4 and 4.2). In this Chapter, although significant difference among sites was recognized in *L** of heartwood color (Table 5.1), data from the two sites were combined to analyze among clone variation of the measured characteristics. For statistical analysis, the same method described in 2.2.4 was employed.

5.3 Results and discussion

5.3.1 Decay resistance

The highest value of mass loss was 29.3% for clone P and R. The lowest value of mass loss was 16.1% for clone V (Table 5.2). In addition, the mean value of mass loss of 26 sample trees from nine clones was 24.7%. Several researchers reported mass loss of teak wood attacked by *T. versicolor* (Yamamoto *et al*. 1998; Bhat and Florence 2003; Bhat *et al*. 2005). Yamamoto *et al*. (1998) reported that mass loss attacked by *T. versicolor* was 3.2% for heartwood of 30-year-old teak trees planted in Malaysia. Mass loss of heartwood attacked by *T. versicolor* was 1.65 – 1.95% from 35-year-old teak trees planted in India (Bhat *et al*. 2005). In addition, mass loss by *T. versicolor* in the heartwood was 11.0, 11.8, and 7.6% for 13-, 21-, and 55-year-old teak trees planted in India, respectively (Bhat and Florence 2003). In the present study, the value of mass loss was higher than that reported by previous researchers (Yamamoto *et al.* 1998; Bhat and Florence 2003; Bhat *et al.* 2005). These differences might be related to the diffrence in exprimental methods for decay test.

Durability of wood depends on several factors, including genetic origin of tree, silviculture, climate, and local environment (Kokutse *et al*. 2006). Table 5.2 shows the statistical values of the mass loss and other measured characteristics. The mass loss was significantly different among nine clones. In addition, the high *R* value was obtained in mass loss. The h^2 of decay resistance ranged from 0.13 to 0.58 in *E. cladocalix* (Bush *et al*. 2011). In the present study, similar result was obtained with that of previous study (Bush *et al*. 2011). Based on these results, it is considered that decay resistance of teak is genetically controlled. Therefore, decay resistance is one of the important criteria for selecting plus trees in teak breeding programs.

5.3.2 Heartwood color

Table 5.2 shows the statistical values of the heartwood color and other measured characteristics. The mean values of L^*, a^*, and b^* were 61.9, 5.6, and 17.9, respectively. In addition, mean values of L^*, a^*, and b^* ranged from 59.0 to 64.3, 4.8 to 6.9, and 16.5 to19.1, respectively. Thulasidas *et al.* (2006) reported that the values of L^*, a^*, and b^* at the heartwood of 35-year-old teak trees planted in India were 52.3 – 56.4, 6.4 – 6.9, and 21.1 – 23.4, respectively. The values of L^*, a^*, and b^* at the inner heartwood of 32-year-old teak trees planted in Indonesia were 54.2, 6.3, and 23.5, respectively (Lukmandaru *et al*. 2009). Moya and Berrocal (2010) reported that the mean values of *L**, *a**, and *b** at the heartwood from 7- to 15-year-old teak trees planted in Costa Rica were 58.2, 10.4, and 25.9, respectively. In addition, Moya and Calvo-Alvarado (2012) also reported that the mean values of *L**, *a**, and *b** from the 7- to 15-year-old teak trees at the different plantation sites in Costa Rica were 59.1, 10.4, and 25.7, respectively. Furthermore, the mean values of *L**, *a**, and *b** at the heartwood of 40 clones of 10-year-old teak planted in Costa Rica were 62.4, 9.5, and 28.6, respectively (Moya and Marín 2011). In the present study, *L** showed relatively higher, and *a**and *b** showed relatively lower values compared to those obtained by previous studies (Thulasidas *et al*. 2006; Moya and Berrocal 2010; Moya and Marín 2011; Moya and Calvo-Alvarado 2012; Lukmandaru *et al*. 2009).

In *E. dunii*, significant differences in wood color were found among half-sib families, although the color variation was very small (Vanclay *et al*. 2008). Montes *et al*. (2008) reported that h^2 of *L**, *b**, and *a** were 0.48, 0.52, and 0.52, respectively, for *Calycophyllum spruceanum*. In addition, Moya and Marín (2011) reported that *L**, *a**, and *b** values were significantly different among 40 clones of 10-year-old teak trees planted in Costa Rica. They also reported that H^2 of *L**, *a**, and *b** were 0.45, 0.36, and 0.36, respectively. In the present study, the *R* of *L** and *a** showed moderate to high values (0.64 for *L** and 0.42 for *a**), although the *R* of *b** could not calculate,. The moderate to high values of *R* for *L** and *b** indicate that these characteristics are also genetically controlled in teak tree.

5.3.3 Quantification of extractives

Table 5.3 shows statistical values of extractive contents. Mean values of ethanol–toluene extract content ranged from 4.8 to 8.2% in each clone. The mean value of the ethanol–toluene extract content was 6.8%. The highest value of ethanol–toluene extract content was 8.2% for clone S, whereas the lowest was 4.8% for clone V. The ethanol extract content was 8.1% of the 30-year-old teak trees planted in Malaysia (Yamamoto *et al.* 1998). Bhat *et al.* (2005) reported that total ethanol–benzene extract content ranged from 12.4 to 16.0% in 35-year-old teak planted in India. In addition, ethanol–benzene extract content at the outer heartwood of 8-, 30-, and 51-year-old teak trees planted in Indonesia were 5.3, 7.0, and 8.0%, respectively

(Lukmandaru and Takahashi 2009). In the present study, the mean value of ethanol–toluene extract content was almost the same with those of previous report (Lukmandaru and Takahashi 2009). Furthermore, moderate value of *R* was obtained for ethanol-toluene extract content in the present study (Table 5.3). The H^2 values of ethanol-benzene extract content were 0.18 and 0.99 in *P. tremuloides* and *P. deltoides*, respectively (Yanchuck *et al.* 1988; Klasnja *et al.* 2003). In the present study, moderate *R* value for extract content was almost similar to those of previous studies (Yanchuck *et al.* 1988; Klasnja *et al.* 2003).

Figures 5.1 to 5.5 shows total ion chromatograms and mass spectra of sample and standard of five extractives in GC-MS analysis Table 5.3 also shows the contents of five extractives, tectoquinone, palmitic acid, lapachol, 2-(hydroxymethyl)anthraquinone, and squalene. The mean content values of tectoquinone, palmitic acid, lapachol, 2-(hydroxymethyl)anthraquinone, and squalene were 5.65, 0.13, 0.78, 1.69, and 1.84 µmol/g, respectively. The tectoquinone content of the 35-year-old teak trees planted in India ranged from 0.23 to 0.32% (10.34 – 14.40 µmol/g) of the ethanol-benzene extract (Thulasidas and Bhat 2007). At the inner heartwood of the 32-year-old teak planted in Indonesia, the contents of tectoquinone, palmitic acid, lapachol, 2-(hydroxymethyl)anthraquinone, and squalene were 0.18, 0.02, 0.02, 0.03, and 0.40% of the oven-dried wood meal (8.01, 0.78, 0.78, 1.25, and 9.73 µmol/g), respectively (Lukmandaru *et al.* 2009). Furthermore, Lukmandaru and Takahashi (2009) also reported that, in the inner heartwood of the 30- and 51-year old teak trees planted in Indonesia, the contents of teqtoquinone, palmitic acid, lapachol, and squalene were 0.19 and 0.30%, 0.06 and 0.04%, 0.10 and 0.03%, and 0.56 and 0.24% (8.50 and 13.50 µmol/g, 2.34 and 1.56 µmol/g, 4.13 and 1.24 µmol/g, and 13.63 and 5.84 µmol/g), respectively. In the present study, mean values of extractive content were lower than those of the previous reports (Thulasidas and Bhat 2007; Lukmandaru *et al.* 2009; Lukmandaru and Takahashi 2009). On the other hand, no significant differences among clones were found in all extractives (Table 5.3). However, low to moderate values of *R* were obtained for the extractive content (Table 5.3).

5.3.4 Relationships between decay resistance and other measured characteristics

It was reported that decay resistance is significantly correlated with wood color in teak (Kokutse *et al*. 2006; Lukmandaru and Takahashi 2008; Moya and Berrocal 2010). Kokutse *et al*. (2006) reported that mass loss of teak wood attacked by *T. versicolor* had significant negative correlations with L^* and b^*, whereas no significant correlation was found between mass loss and b^* value. Furthermore, mass loss attacked by *T. versicolor* was found to have significant positive correlation with L^* value, significant negative correlation with b^*, and no correlation with a^* in teak wood (Moya and Berrocal 2010). In the present study, as shown in Table 5.4, no significant correlation was found between mass loss and heartwood color.

In teak wood, it is considered that the extractives are important for the natural durability (Narayanamurti *et al*. 1962; Yamamoto *et al*. 1998; Bhat *et al*. 2005; Lukmandaru and Takahashi 2008). Particularly, tectoquinone was identified as a bioactive compound for the inhibition of brown-rot fungus *Coniophora puteana* (Haupt *et al*. 2003). In addition, mass loss attacked by brown-rot fungus *Antrodia* sp. showed highly significant negative correlations with 2-(hydroxymethyl)anthraquinone (r = –0.82) and tectoquinone (r = –0.79) (Niamké *et al*. 2011). In the present study, as shown in Table 5.4, significant correlation was only found between mass loss and 2-(hydroxymethyl)anthraquinone (r = –0.747). However, the individual chemical composition of the extractives, even if present in small amounts, is more vital than the total quantity of the extractives in determining the durability of teak wood (Haupt *et al*. 2003). In addition, higher amounts of extractives may not necessarily contribute to higher natural durability (Hillis 1987; Yamamoto and Hong 1989). Therefore, further research is needed to clarify the more detailed relationships between mass loss and other characteristics (wood color, and extractive contents) in plantation grown teak wood.

5.4 Summary

In this Chapter, the variations of decay resistance, heartwood color, and extractive contents were clarified for the total 26 trees from nine clones of 12-year-old teak trees planted in Indonesia. In addition, the relationships between mass loss and other characteristics were also clarified. Significant differences among clones were found in decay resistance (mass loss), and L^* and a^* values of heartwood. Moderate to high values of *R* were obtained for these characteristics. It is, therefore, suggested that these characteristics are genetically controlled in teak trees. Furthermore, no significant differences were found in *b** value of heartwood and ethanol-toluene extract content. In addition, low to moderate values of *R* were obtained in extractive contents. Furthermore, significantly negative correlation was found between decay resistance (mass loss) and 2-(hydroxymethyl)anthraquinone content, suggesting that this compound might be related to decay resistance of teak. Based on these results, decay resistance, heartwood color, and 2-(hydroxymethyl)anthraquinone are important factors to improve the wood durability in teak breeding programs.

Table 5.1 Comparison of mean values of mass loss, heartwood color, and extractive content of clone Q between the two clonal test sites

Character	Cepu (n = 3)		Ciamis (n = 2)		Significance between two sites
	Mean	SD	Mean	SD	
Mass loss (%)	26.0	1.0	26.9	0.8	ns
*L**	63.9	0.9	60.4	0.5	*
*a**	4.9	0.2	6.6	0.9	ns
*b**	18.5	0.5	19.9	0.6	ns
Ethanol-toluene extract (%)	6.4	0.3	6.3	1.6	ns
Tectoquinone (µmol/g)	1.40	1.67	1.36	0.26	ns
Palmitic acid (µmol/g)	0.05	0.06	0.02	0.00	ns
Lapachol (µmol/g)	0.30	0.22	0.11	0.04	ns
2-(Hydroxymethyl)-anthraquinone (µmol/g)	0.38	0.30	0.39	0.11	ns
Squalene (µmol/g)	0.61	0.29	0.44	0.54	ns

Note: *n*, number of trees; SD, standard deviation; ns, no significance; *, significance at 5% level.

Table 5.2 Statistical values of mass loss and heartwood color of each clone

Clone code	n	Mass loss (%)		Heartwood color					
				L^*		a^*		b^*	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
P	2	29.3	2.0	59.9	1.1	6.1	0.2	16.5	0.7
Q	5	26.0	1.1	62.4	1.9	5.5	1.1	19.1	0.9
R	3	29.3	4.6	59.3	1.9	6.9	0.5	17.4	2.0
S	3	20.7	2.0	59.0	1.0	6.2	0.3	17.8	1.7
T	3	25.2	2.4	62.7	0.4	5.2	0.3	18.0	0.6
U	3	24.5	5.9	61.7	0.6	5.2	0.6	17.9	0.8
V	2	16.1	0.1	64.3	0.7	4.8	0.4	17.5	0.5
W	2	26.0	4.3	64.3	0.4	5.1	0.3	18.9	0.8
X	3	24.9	0.6	63.0	1.5	5.1	0.6	17.9	0.9
Mean/total	26	24.7	4.1	61.9	2.0	5.6	0.7	17.9	0.8
Significance among clones		**		**		*		ns	
σ^2_c		11.25		3.26		0.31		-	
σ^2_e		9.35		1.83		0.43		1.74	
R		0.55		0.64		0.42		-	

Note: n, number of trees; SD, standard deviation; **, significance at 1% level; *, significance at 5% level; ns, no significance; σ^2_c, variance component of clone; σ^2_e, variance component of environment; R, repeatability.

Table 5.3 Statistical values of extractive content ineach clone

Clone code	n	Ethanol-toluene extract (%)		Extractive (μmol/g)									
				Tectoquinone		Palmitic acid		Lapachol		2-(Hydroxymethyl)-anthraquinone		Squalene	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
P	2	7.5	0.7	4.43	1.58	0.05	0.01	0.24	0.15	1.25	1.05	1.97	0.05
Q	5	6.5	0.9	5.54	3.33	0.15	0.19	0.90	0.76	1.52	0.88	2.27	1.49
R	3	7.7	2.0	4.42	1.14	0.05	0.01	0.30	0.04	1.71	1.33	1. 23	0.59
S	3	8.2	1.7	5.79	0.22	0.05	0.00	0.79	0.12	2.86	0.34	0.72	0.24
T	3	7.3	0.6	3.64	1.24	0.05	0.00	0.58	0.15	0.81	0.48	1.51	0.92
U	3	6.7	0.8	10.00	6.18	0.31	0.09	1.36	0.33	1.94	0.97	2.49	1.65
V	2	6.4	0.5	7.02	6.58	0.32	0.33	1.00	0.28	2.92	3.12	3.73	0.56
W	2	4.8	0.8	5.66	1.16	0.12	0.07	0.74	0.10	1.06	0.07	1.27	0.16
X	3	6.4	0.9	4.35	1.50	0.10	0.04	1.11	0.45	1.12	0.57	1.36	0.68
Mean/total	26	6.8	1.0	5.65	1.92	0.13	0.11	0.78	0.36	1.69	0.76	1.84	0.90
Significance among clones		ns		ns		ns		ns		ns		ns	
σ^{2}_{c}		0.45		0.07		0.01		0.07		0.10		0.35	
σ^{2}_{e}		1.27		10.48		0.02		0.18		1.21		1.06	
R^2		0.26		0.01		0.23		0.26		0.08		0.25	

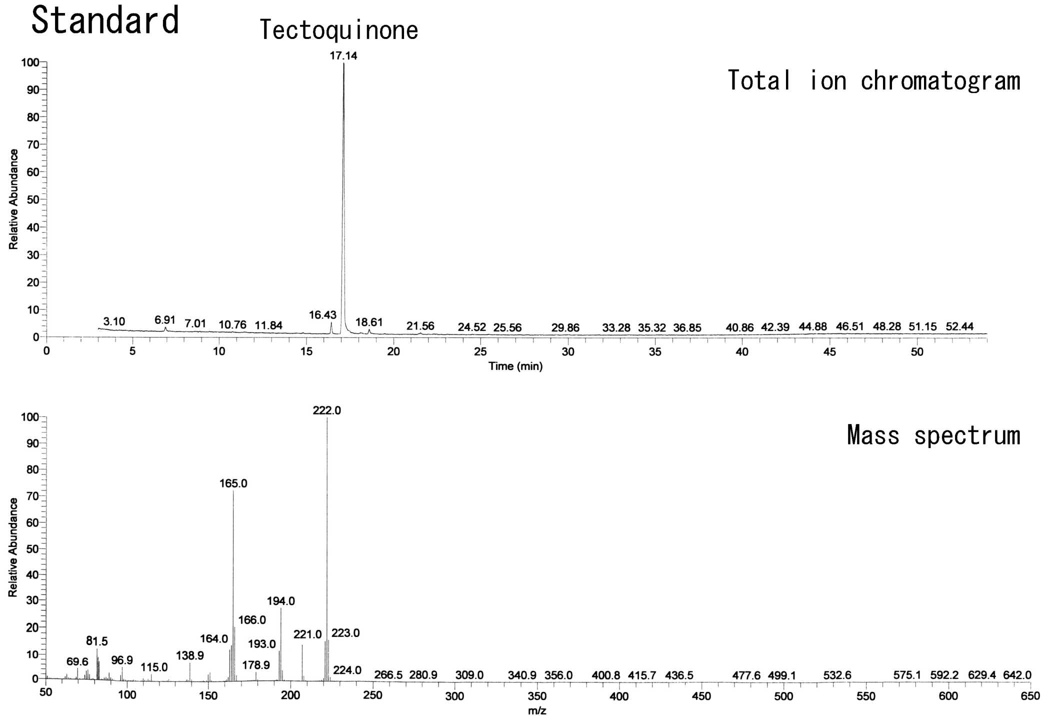
Note: n, number of trees; SD, standard deviation; ns, no significance; σ^{2}_{c}, variance component of clone; σ^{2}_{e}, variance component of environment; R^2, repeatability.

Table 5.4 Correlation coefficients between mass loss and measured characteristics

Character		Correlation coefficient	
Heartwood color	*L**	-0.393	ns
	*a**	0.505	ns
	*b**	-0.091	ns
Ethanol-toluene extract		0.070	ns
Tectoquinone		-0.408	ns
Palmitic acid		-0.586	ns
Lapachol		-0.553	ns
2-(Hidroxymethyl)anthraquinone		-0.747	*
Squalene		-0.490	ns

Note: *, significance at 5% level; ns, no significance.

Standard



Sample

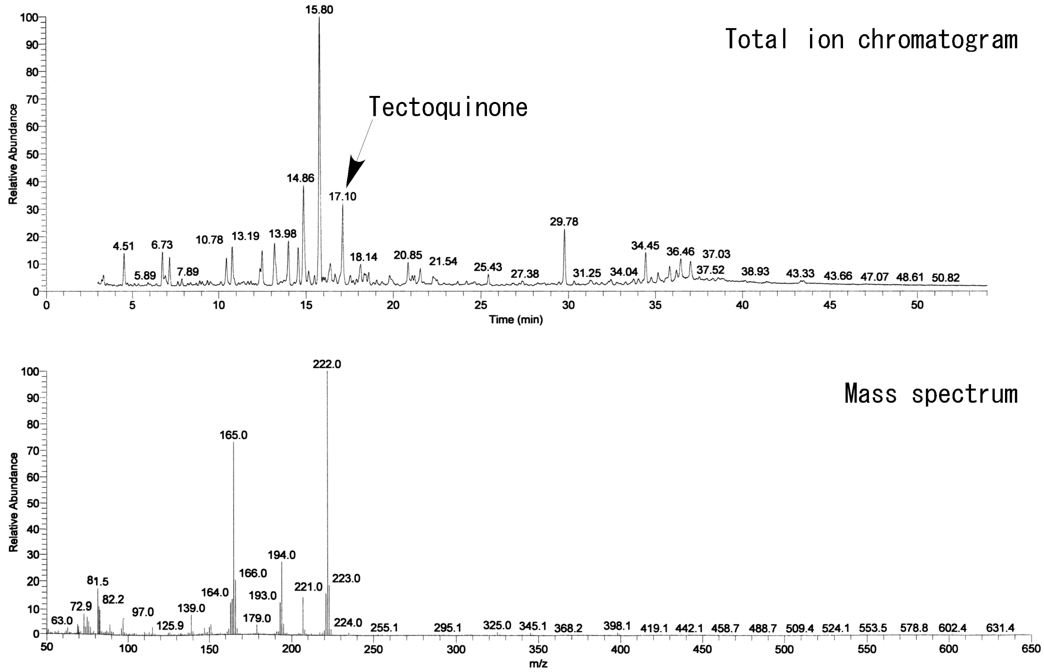


Fig. 5.1 Total ion chromatograms and mass spectra of sample and standard of tectoquinone in GC-MS analysis

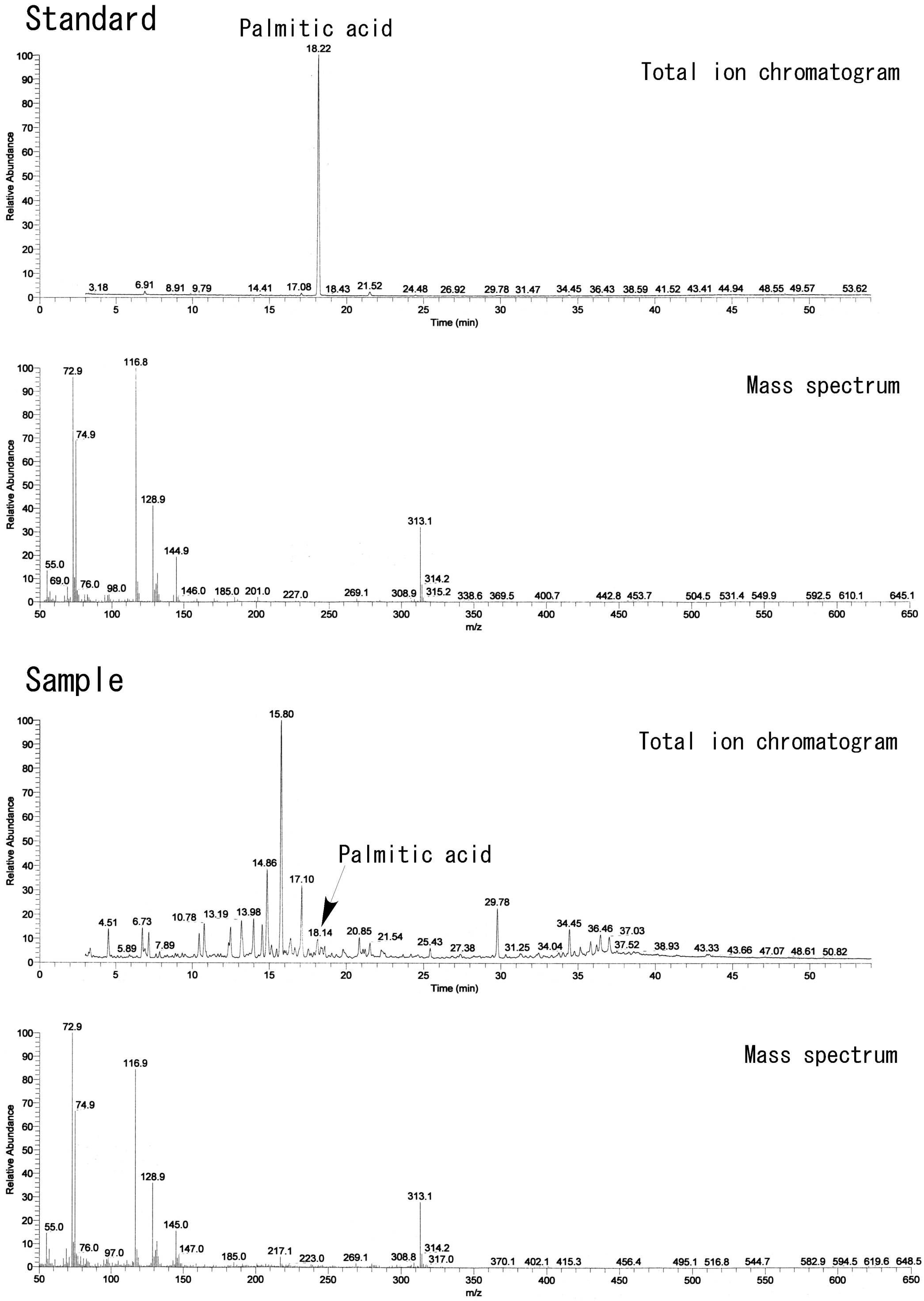
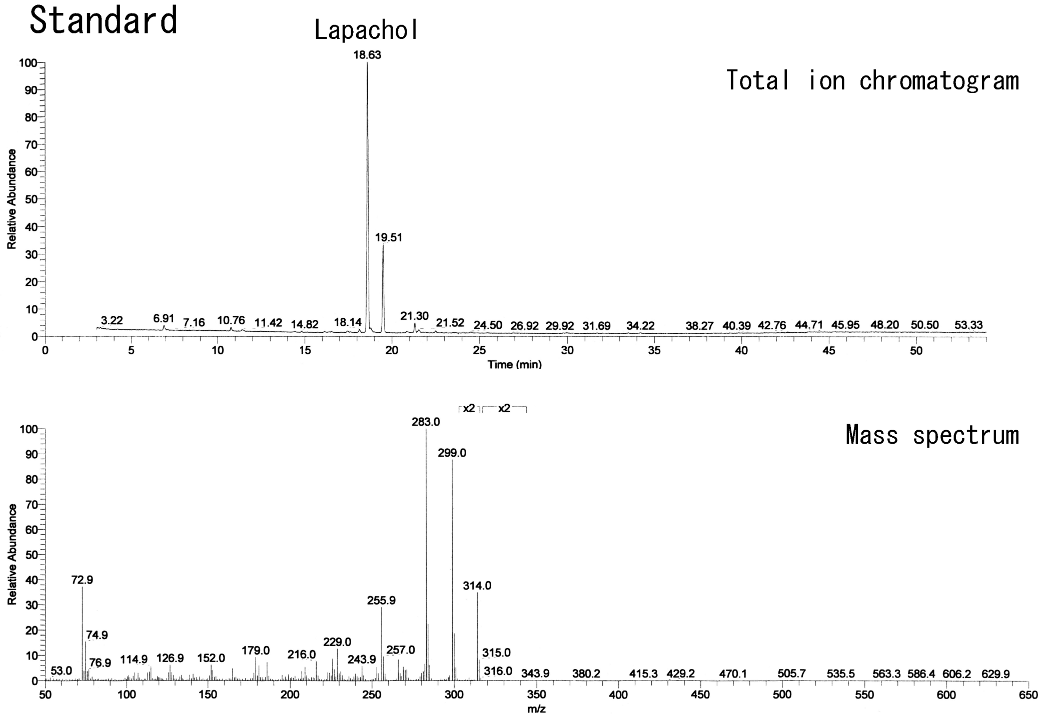


Fig. 5.2 Total ion chromatograms and mass spectra of sample and standard of palmitic acid in GC-MS analysis

Standard



Sample

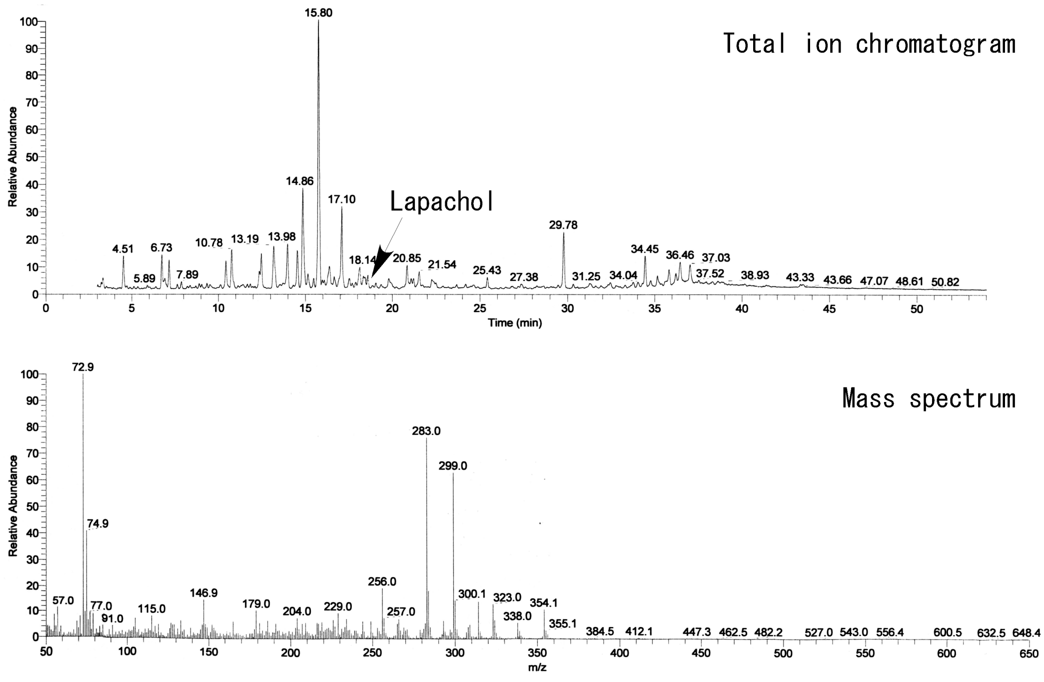
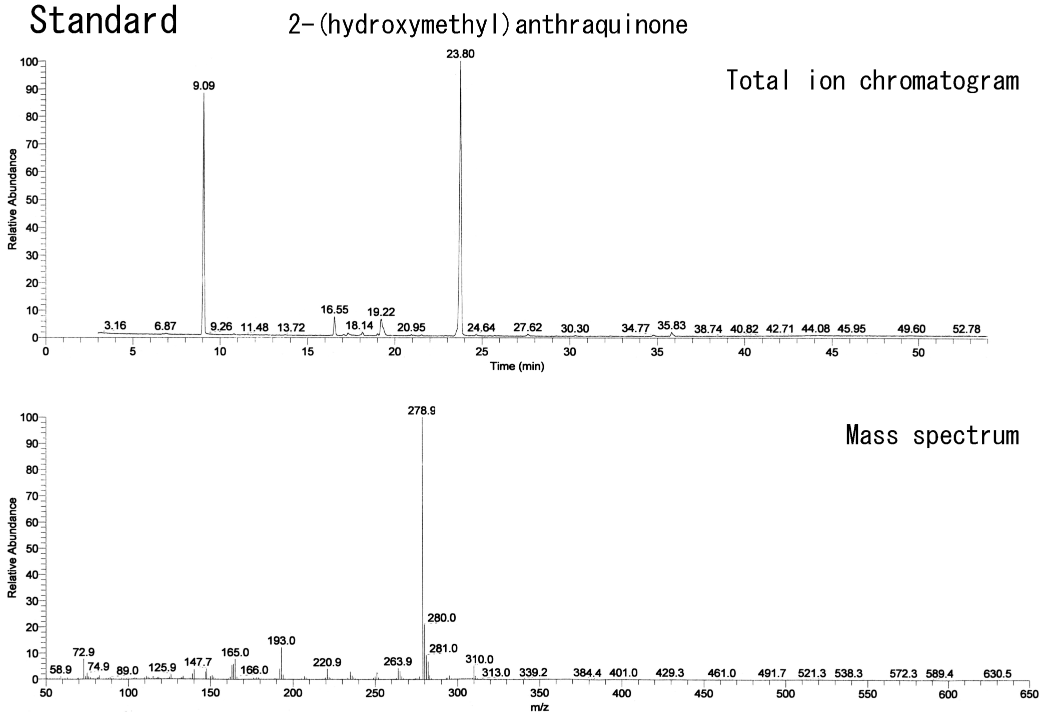


Fig. 5.3 Total ion chromatograms and mass spectra of sample and standard of lapachol in GC-MS analysis

Standard



Sample

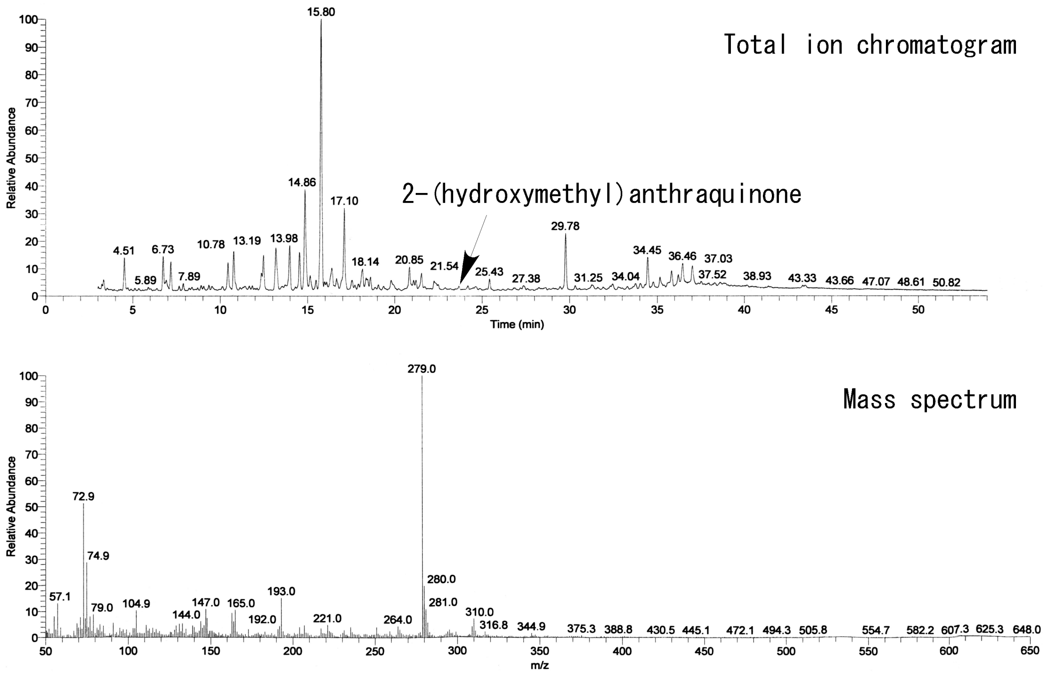


Fig. 5.4 Total ion chromatograms and mass spectra of sample and standard of 2-(hydroxymethyl)anthraquinone in GC-MS analysis

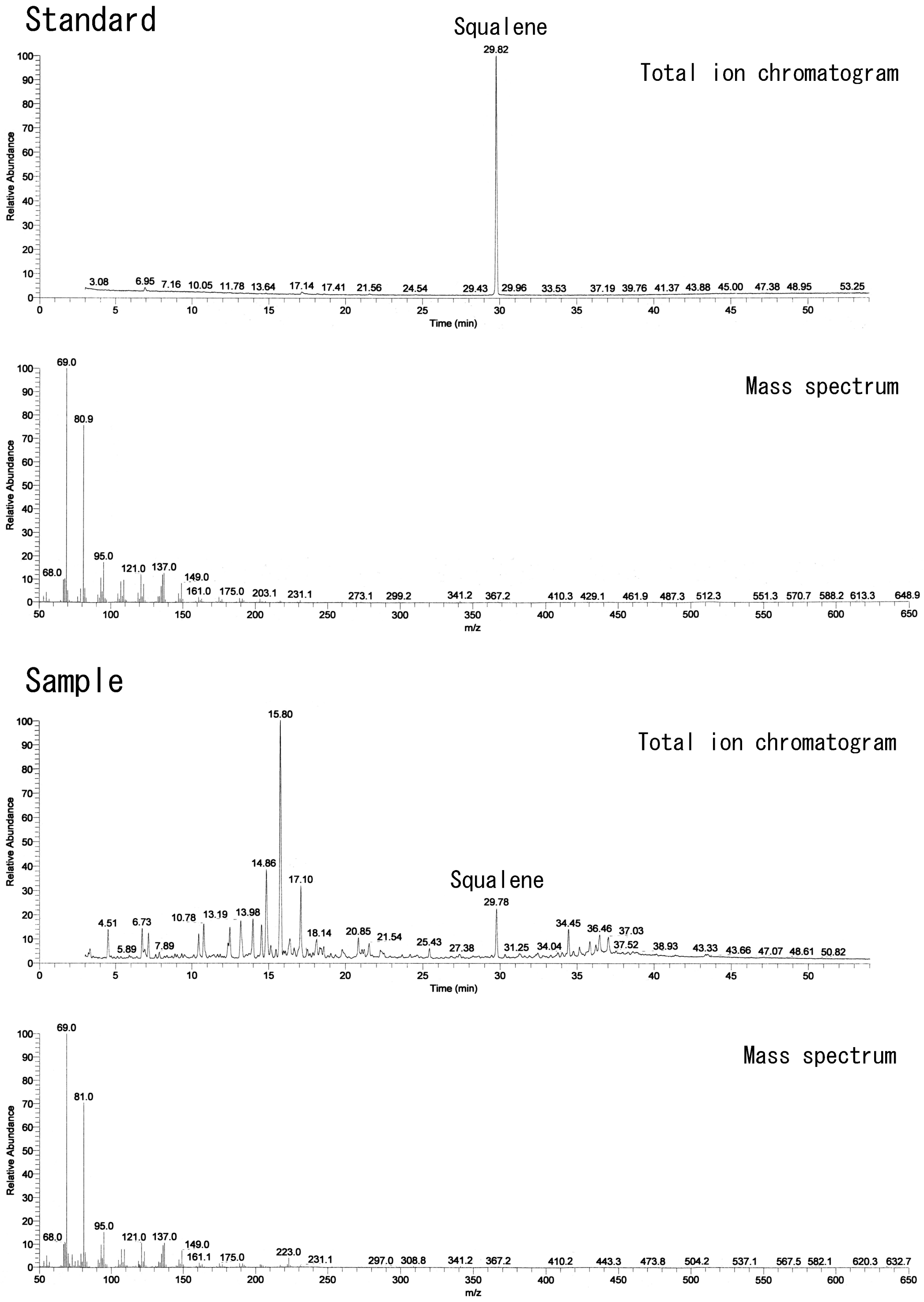


Fig. 5.5 Total ion chromatograms and mass spectra of sample and standard of squalene in GC-MS analysis

Chapter 6 Conclusion

Teak (*Tectona grandis* L.f.) is an important commercial plantation species, and the demand for teak wood is increasing in Indonesia. However, the total wood production of this species is decreasing, because teak wood resources have declined and the productivity of the plantations is low. Therefore, tree breeding programs have been developed to produce more productive teak forest in Indonesia, such as establishment of clonal test sites and seed provenance test sites. In this thesis, the variations of growth characteristics and wood properties were investigated among clones and seed provenances of teak trees, and four studies were presented as follows: (1) variation of growth characteristics, SWV, and *P* among 15 clones of 12-year-old teak trees, (2) variation of growth characteristics, SWV, and *P* among 21 seed provenances of 24-year-old teak tree, (3) variation of anatomical characteristics and wood properties among 9 clones of 12-year-old teak trees, and (4) variation of decay resistance, wood color, extractive content among nine clones of 12-year-old teak trees.

The first study focused on the variation of growth characteristics (*D*, TH, and *V*), SWV, and *P* among 15 clones of 12-year-old teak trees planted at two different sites in Indonesia. In addition, their *R* values, interactions between genotype and environment, and correlations between measured characteristics were also clarified. Significant differences of all measured characteristics were found among 15 clones at both sites. Their *R* values were relatively moderate to high in both sites. These results indicate that these characteristics are closely related to genetic factors. Significant interactions between genotype and environment were found in all measured characteristics, suggesting that interactions between genotype and environment should be considered when the teak plantations are established in Indonesia. In addition, SWV and *P* showed lower interaction between genotype and environment than growth characteristics. No significant correlations were found between growth characteristics and SWV, suggesting that SWV is independent of growth characteristics of teak trees. Based on these results, wood properties and growth characteristics of teak trees can be improved by application of an appropriate tree breeding program.

The second study also dealt with the variation of growth characteristics (*D*, TH, and *V*), SWV, and *P* among 21 seed provenances of 24-year-old teak trees planted in Indonesia. The *R* values and correlations between the measured characteristics were also determined. Significant differences for all measured characteristics were observed among provenances, indicating that these characteristics are genetically controlled. Repeatabilities of growth characteristics, SWV, and *P* showed moderate values. These results indicate potentials for improving both growth characteristics and wood properties of teak trees with the help of breeding programs. Highly significant positive correlations were observed among the growth characteristics, suggesting that they are closely related. In contrast, no significant correlations were observed between the growth characteristics and SWV, indicating that they are independent each other. It is concluded that mechanical properties are also important criteria for selecting plus trees in teak tree breeding programs. Principal component analysis revealed that seed provenances from Indonesia (Bangilan, Deling, and Randublatung) and India (Malabar and Central Province) had high scores of growth characteristics and SWV.

The third study clarified the variation of anatomical characteristics and wood properties among nine clones of 12-year-old teak trees planted in Indonesia. Their *R* values and relationships among characteristics were also clarified. Clone P showed the lowest values of VD, FD, and VEL, and the highest values of FWT, BD, and CS. The mean values of VD, FWT, FD, VEL, FL, BD, and CS were 188 μm, 2.78 μm, 23.4 μm, 0.284 mm, 1.42 mm, 0.51 g/cm^3, and 37.5 MPa, respectively. Significant differences among the nine clones were found in VEL, BD, and CS. Moderate to high values of *R* were obtained for FD, VEL, BD, and CS, indicating that these characteristics are genetically controlled. Radial variation of FL with respect to relative distance from the pith showed almost the same pattern for the two radial growth rate categories, suggesting that xylem maturation depends on cambial age rather than radial growth in teak trees. It is, therefore, concluded that after forming mature wood, intensive silvicultural practices should be applied to produce as much mature wood as possible in teak trees.

The fourth study investigated the variation of decay resistance, wood color, and extractive contents among nine clones of 12-year-old teak trees planted in Indonesia. Furthermore, *R* values and relationships between mass loss and other characteristics were also clarified. Significant differences among clones were found in mass loss decayed by *Trametes versicolor* and heartwood color (*L** and *a** values). Moderate to high values of *R* were obtained for these characteristics. It is, therefore,suggest that these characteristics are genetically controlled in teak trees. No significant differences were found in *b** value of heartwood and extractive contents. In addition, low to moderate values of *R* were found in extractive contents. Furthermore, significantly negative correlation was found between decay resistance (mass loss) and 2-(hydroxymethyl)anthraquinone content, suggesting that this compound might be related to decay resistance of teak. Based on these results, decay resistance, heartwood color and 2-(hydroxymethyl)anthraquinone content are important factors to improve the wood durability in teak breeding programs.

In the present study, the growth characteristics and wood properties of teak varied among clones and seed provenances. In Indonesia, breeding programs of teak only focus on growth characteristics, such as stem diameter, tree height, stem form, and etc. However, wood quality is one of the important criteria in breeding program, because it is related to the quality of the end product. Therefore, based on these results, it is suggested that growth characteristics and wood quality can be improved by application of an appropriate tree breeding program. Furthermore, it is indicated that using a selection index integrating more than a single property would be effective rather than using a single property in teak trees. In the future, the use of better planting materials from breeding programs and intensive silvicultural practices will produce more trees with good growth characteristics, high wood quality, and shorter rotation age in teak plantations in Indonesia.

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References

Abdi H, Williams LJ (2010) Principal component analysis. WIREs Computational Statistics 2: 433-459

Atmasari N (2012) 6 bulan, jati JUN tumbuh tiga meter. http://www.harianjogja.com/baca/2012/05/11/6-bulan-jati-jun-tumbuh-tiga-meter-184950. Accessed on April 21, 2014 (in Indonesian)

Bailey JD, Harjanto NA (2005) Teak (*Tectona grandis* L.) tree growth, stem quality and health in coppiced plantations in Java, Indonesia. New Forests 30: 55-65

Bermejo I, Cañellas I, Miguel AS (2004) Growth and yield models for teak plantations in Costa Rica. Forest Ecology and Management 189: 97-110

Bhat KM, Florence EJM (2003) Natural decay resistance of juvenile teak wood grown in high input plantations. Holzforschung 57: 453-455

Bhat KM, Priya PB (2004) Influence of provenance variation on wood properties of teak from the Western Ghat region in India. IAWA Journal 25: 273-282

Bhat KM, Priya PB, Rugmini P (2001) Characterisation of juvenile wood in teak. Wood Science and Technology 34: 517-532

Bhat KM, Thulasidas PK, Florence EJM, Jayaraman K (2005) Wood durability of home-garden teak against brown-rot and white-rot fungi. Trees 19: 654-660

Brashaw BK, Bucur V, Divos F, Gonçalves R, Lu J, Meder R, Pellerin RF, Potter S, Ross RJ, Wang X, Yin Y (2009) Nondestructive testing and evaluation of wood: A worldwide research update. Forest Products Journal 59: 7-14

Bucur V (2006) Accoustics of wood. Springer-Verlag Berlin, Heidelberg, New York, pp 1-393

Bush D, McCarthy K, Meder R (2011) Genetic variation of natural durability traits in *Eucalyptus cladocalyx* (sugar gum). Annals of Forest Science 68: 1057-1066

Callister AN, Collins SL (2008) Genetic parameter estimates in a clonally replicated progeny test of teak (*Tectona grandis* Linn. f.). Tree Genetics & Genomes 4: 237-245

Chaix G, Monteuuis O, Garcia C, Alloysius D, Gidiman J, Bacilieri R, Goh DKS (2011) Genetic variation in major phenotypic traits among diverse genetic origins of teak (*Tectona grandis* L.f.) planted in Taliwas, Sabah, East Malaysia. Annals of Forest Science 68: 1015-1026

Chowdhury MQ, Ishiguri F, Hiraiwa T, Matsumoto K, Takashima Y, Iizuka K, Yokota S, Yoshizawa N (2012) Variation in anatomical properties and correlations with wood density and compressive strength in *Casuarina equisetifolia* growing in Bangladesh. Australian Forestry 75: 95-99

Chowdhury MQ, Ishiguri F, Iizuka K, Hiraiwa T, Matsumoto K, Takashima Y, Yokota S (2009a) Wood property variation in *Acacia auriculiformis* growing in Bangladesh. Wood and Fiber Science 41: 359-365

Chowdhury MQ, Ishiguri F, Iizuka K, Takashima Y, Matsumoto K, Hiraiwa T, Ishido M, Sanpe H, Yokota S, Yoshizawa N (2009b) Radial variations of wood properties in *Casuarina equisetifolia* growing in Bangladesh. Journal of Wood Science 55: 139-143

Cordero LDP, Kanninen M (2003) Heartwood, sapwood and bark content, and wood dry density of young and mature teak (*Tectona grandis*) trees grown in Costa Rica. Silva Fennica 37: 45-54

Costa e Silva J, Borralho NMG, Araújo JA, Vaillancourt RE, Potts BM (2009) Genetic parameters for growth, wood density and pulp yield in *Eucalyptus globulus*. Tree Genetics & Genomes 5: 291-305

Costa e Silva J, Nielsen UB, Roulund H (1994) Sitka spruce clonal performance with special reference to basic density. Silvae Genetica 43: 82-91

Danarto S, Hardiyanto EB (2000) Results of the progeny test of teak at 12 years of age at Jember, East Java. In: Proceedings of third regional seminar on teak. Potentials and opportunities in marketing and trade of plantation teak: Challenge for the new millenium. Faculty of Forestry, Gadjah Mada University, Yogyakarta, pp 249-253

Denis M, Favreau B, Ueno S, Camus-Kulandaivelu L, Chaix G, Gion JM, Nourrisier-Mountou S, Polidori J, Bouvet JM (2013) Genetic variation of wood chemical traits and association with underlying genes in *Eucalyptus urophylla*. Tree Genetics & Genomes 9: 927-942

Dickson RL, Raymond CA, Joe W, Wilkinson CA (2003) Segregation of *Eucalyptus dunnii* logs using acoustics. Forest Ecology and Management 179: 243-251

Evans J, Turnbull JW (2004) Plantation forestry in the tropics. Third edition. Oxford University Press, New York, pp 1-467

Falconer DS (1989) Introduction to quantitative genetics. Third edition. Longman

Scientific & Technical, England, pp 1-438

Goh DKS, Chaix G, Baillères H, Monteuuis O (2007) Mass production and quality control of teak clones for tropical plantations: The Yayasan Sabah group and CIRAD joint project as a case study. Bois et Forêts des Tropiques 293: 65-75

Greaves BL, Borralho NMG, Raymond CA, Farrington A (1996) Use of a Pilodyn for the indirect selection of basic density in *Eucalyptus nitens*. Canadian Journal of Forest Research 26: 1643-1650

Hai PH, Hannrup B, Harwood C, Jansson G, Ban DV (2010) Wood stiffness and strength as selection traits for sawn timber in *Acacia auriculiformis*. Canadian Journal of Forest Research 40: 322-329

Hai PH, Jansson G, Harwood C, Hannrup B, Thinh HH (2008) Genetic variation in growth, stem straightness and branch thickness in clonal trials of *Acacia auriculiformis* at three contrasting sites in Vietnam. Forest Ecology and Management 255: 156-167

Hansen CP (2000) Application of the Pilodyn in forest tree improvement. Danida Forest Seed Centre, Humlebaek, pp 1-11

Hansen JK, Roulund H (1997) Genetic parameters for spiral grain, stem form, Pilodyn and growth in 13 years old clones of Sitka spruce (*Picea sitchensis* (Bong.) Carr.). Silvae Genetica 46: 107-113

Haupt M, Leithoff H, Meier D, Puls J, Richter HG, Faix O (2003) Heartwood extractives and natural durability of plantation-grown teakwood (*Tectona grandis* L.) – a case study. Holz als Roh- und Werkstoff 61: 473-474

Hein PRG (2011) Genetic control of wood traits in *Eucalyptus* plantations: The effect of microfibril angle on wood traits and implications for selection. Südwestdeutscher, Saarbrücken, pp 1-168

Hidayati F, Ishiguri F, Iizuka K, Makino K, Marsoem SN, Yokota S (2014) Among-clone varaitions of anatomical characteristics and wood properties in *Tectona grandis* planted in Indonesia. Wood and Fiber Science 46 (In Press)

Hidayati F, Ishiguri F, Iizuka K, Makino K, Takashima Y, Danarto S, Winarni WW, Irawati D, Na'iem M, Yokota S (2013a) Variation in tree growth characteristics, stress-wave velicty, and Pilodyn penetration of 24-year-old teak (*Tectona grandis*) trees originating in 21 seed provenances planted in Indonesia. Journal of Wood Science 59: 512-516

Hidayati F, Ishiguri F, Iizuka K, Makino K, Tanabe J, Marsoem SN, Na'iem M, Yokota S, Yoshizawa N (2013b) Growth characteristics, stress-wave velocity, and Pilodyn penetration of 15 clones of 12-year-old *Tectona grandis* trees planted at two different sites in Indonesia. Journal of Wood Science 59: 249-254

Hillis WE (1987) Heartwood and tree exudates. Springer-Verlag, Berlin, Heidelberg, New York, London, Paris, Tokyo, pp 1-268

Honjo K, Furukawa I, Sahri MH (2005) Radial variation of fiber length increment in *Acacia mangium*. IAWA Journal 26: 339-352

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. Mokkuzai Gakkaishi 46: 189-196 (in Japanese with English summary)

Iki T, Tamura A, Nishioka N, Abe M, Iizuka K (2009) Longitudinal changes of basic density and non-destructive quality evaluation using the Pilodyn in todomatsu (*Abies sachalinensis*) plus tree clones. Mokkuzai Gakkaishi 55: 18-28 (in Japanese with English summary)

Indira EP, Bhat KM (1998) Effects of site and place of origin on wood density of teak (*Tectona grandis*) clones. Journal of Tropical Forest Science 10: 537-541

Ishiguri F, Diloksumpun S, Tanabe J, Iizuka K, Yokota S (2013) Stress-wave velocity of trees and dynamic Young's modulus of logs of 4-year-old *Eucalyptus camaldulensis* trees selected for pulpwood production in Thailand. Journal of Wood Science 59: 506-511

Ishiguri F, Eizawa J, Saito Y, Iizuka K, Yokota S, Priadi D, Sumiasri N, Yoshizawa N (2007) Variation in the wood properties of *Paraserianthes falcataria* planted in Indonesia. IAWA Journal 28: 339-348

Ishiguri F, Eizawa J, Saito Y, Iizuka K, Yokota S, Yoshizawa N (2006) Comparison of wood properties of hinoki (*Chamaecyparis obtusa*) small diameter logs collected from different tree ages and heights. Mokuzai Gakkaishi 52: 383-388 (in Japanese with English summary)

Ishiguri F, Hiraiwa T, Iizuka K, Yokota S, Priadi D, Sumiasri N, Yoshizawa N (2009) Radial variation of anatomical characteristics in *Paraserianthes falcataria* planted in Indonesia. IAWA Journal 30: 343-352

Ishiguri F, Matsui R, Iizuka K, Yokota S, Yoshizawa N (2008) Prediction of the mechanical properties of lumber by stress-wave velocity and Pilodyn penetration of 36-year-old Japanese larch trees. Holz als Roh- und Werkstoff 66: 275-280

Ishiguri F, Takeuchi M, Makino K, Wahyudi I, Takashima Y, Iizuka K, Yokota S, Yoshizawa N (2012) Cell morphology and wood properties of *Shorea acuminatissima* planted in Indonesia. IAWA Journal 33: 25-38

Ishiguri F, Wahyudi I, Takeuchi M, Takashima Y, Iizuka K, Yokota S, Yoshizawa N (2011) Wood properties of *Pericopsis mooniana* grown in a plantation in Indonesia. Journal of Wood Science 57: 241-246

Jayawickrama KJS (2001) Breeding radiata pine for wood stiffness: review and analysis. Australian Forestry 64: 51-56

Kedharnath S, Chacko VJ, Gupta SK, Matthews JD (1963) Geographic and individual tree variation in some wood characters of teak (*Tectona grandis* L.f.): I. Fibre length. Silvae Genetica 12: 181-187

Kim NT, Ochiishi M, Matsumura J, Oda K (2008) Variation in wood properties of six natural acacia hybrid clones in northern Vietnam. Journal of Wood Science 54: 436-442

King JN, Yeh FC, Heaman JCh, Dancik BP (1988) Selection of wood density and diameter in controlled crosses of coastal Douglas-fir. Silvae Genetica 37: 152-157

Kjaer ED, Kajornsrichon S, Lauridsen EB (1999) Heartwood, calcium and silica content in five provenances of teak (*Tectona grandis* L.). Silvae Genetica 48: 1-3

Klasnja B, Kopitovic S, Orlovic S (2003) Variability of some wood properties of eastern cottonwood (*Populus deltoides* Bartr.) clones. Wood Science and Technology 37: 331-337

Kojima M, Yamamoto H, Yoshida M, Ojio Y, Okumura K (2009) Maturation property of fast-growing hardwood plantation species: A view of fiber length. Forest Ecology and Management 257: 15-22

Kokutse AD, Stokes A, Baillères H, Kokou K, Baudasse C (2006) Decay resistance of Togolese teak (*Tectona grandis* L.f) heartwood and relationship with colour. Trees 20: 219-223

Kollert W, Cherubini L (2012) Teak resources and market assessment 2010 (*Tectona* *grandis* Linn. F.). http://www.fao.org/docrep/015/an537e/an537e/an537e00.pdf. Accessed on March 22, 2014

Kumar S, Jayawickrama KJS, Lee J, Lausberg M (2002) Direct and indirect measures of stiffness and strength show high heritability in a wind-pollinated radiata pine progeny test in New Zealand. Silvae Genetica 51: 256-261

Lukmandaru G, Ashitani T, Takahashi K (2009) Color and chemical characterization of partially black-streaked heartwood in teak (*Tectona grandis*). Journal of Forestry Research 20: 377-380

Lukmandaru G, Takahashi K (2008) Variation in the natural termite resistance of teak (*Tectona grandis* Linn.fil.) wood as a function of tree age. Annals of Forest Science 65: 708. DOI: 10.1051/forest:2008047

Lukmandaru G, Takahashi K (2009) Radial distribution of quinones in plantation teak (*Tectona grandis* L.f.). Annals of Forest Science 66: 605. DOI: 10.1051/forest/2009051

Makino K, Ishiguri F, Wahyudi I, Takashima Y, Iizuka K, Yokota S, Yoshizawa N (2012) Wood properties of young *Acacia mangium* trees planted in Indonesia. Forest Products Journal 62: 102-106

Martawijaya A, Kartasujana I, Kadir K, Prawira SA (2005) Atlas kayu Indonesia: Jilid I. Departemen Kehutanan, Bogor, Indonesia, pp 1-171 (in Indonesian)

Matsumoto K, Ishiguri F, Iizuka K, Yokota S, Habu N, Yoshizawa N (2010b) Evaluation of compressive strength of decayed wood in *Magnolia obovata*. Arboriculture & Urban Forestry 36: 81-85

Matsumoto K, Ishiguri F, Wahyudi I, Takashima Y, Shimizu K, Iizuka K, Yokota S, Yoshizawa N (2010a) Application of Fractometer for wood property evaluation in five Indonesian plantation species. Bulletin of Utsunomiya University Forest 46: 1-6

Mawardi P (2012) Kaya dari investasi jati barokah. PT AgroMedia Pustaka, Jakarta, pp 1-104 (in Indonesian)

Montes CS, Hernández RE, Beaulieu J, Weber JC (2008) Genetic variation in wood color and its correlations with tree growth and wood density of *Calycophyllum spruceanum* at an early age in the Peruvian Amazon. New Forests 35: 57-73

Monteuuis O, Goh DKS, Garcia C, Alloysius D, Gidiman J, Bacilieri R, Chaix G (2011) Genetic variation of growth and tree quality traits among 42 diverse genetic origins of *Tectona grandis* planted under humid tropical conditions in Sabah, East Malaysia. Tree Genetics & Genomes 7: 1263-1275

Mosedale JR, Charrier B, Janin G (1996) Genetic control of wood colour, density and heartwood ellagitannin concentration in European oak (*Querqus petraea* and *Q. robur*). Forestry 69: 111-124

Moura VPG, Barnes RD, Birks JS (1987) A comparison of three methods of assessing wood density in provenances of *Eucalyptus camaldulensis* Dehnh. and other *Eucalyptus* species in Brazil. Australian Forest Research 17: 83-90

Moya R, Berrocal A (2010) Wood colour variation in sapwood and heartwood of young trees of *Tectona grandis* and its relationship with plantation characteristics, site, and decay resistance. Annals of Forest Science 67: 109. DOI 10.1051/forest/2009088

Moya R, Calvo-Alvarado J (2012) Variation of wood color parameters of *Tectona grandis* and its relationship with physical environmental factors. Annals of Forest Science. 69: 947-959

Moya R, Marín JD (2011) Grouping of *Tectona grandis* (L.f.) clones using wood color and stiffness. New Forests 42: 329-345

Moya R, Perez D (2008) Effect of physical and chemical soil properties on physical wood characteristics of *Tectona grandis* plantations in Costa Rica. Journal of Tropical Forest Science 20: 147-155

Muneri A, Raymond CA (2000) Genetic parameters and genotype-by-environment interactions for basic density, Pilodyn penetration and stem diameter in *Eucalyptus globulus*. Forest Genetics 7: 317-328

Muneri A, Raymond CA (2001) Nondestructive sampling of *Eucalyptus globulus* and *E. nitens* for wood properties; II. Fibre length and coarseness. Wood Science and Technology 35: 41-56

Na’iem M (2000) Early performance of clonal tests of teak. In: Proceeding of third regional seminar on teak. Potentials and opportunities in marketing and trade of plantation teak: Challenge for the new millennium. Faculty of Forestry Gadjah Mada University, Yogyakarta, pp 271-275

Nanami N, Nakamura N, Arima T, Okuma M (1993) Measuring the properties of standing trees with stress waves III. Evaluating the properties of standing trees for some forest stands. Mokkuzai Gakkaishi 39: 903-909 (in Japanese with

English summary)

Narayanamurti D, George J, Pant HC, Singh J (1962) Extractives in teak. Silvae Genetica 11: 57-62

Niamké FB, Amusant N, Charpentier JP, Chaix G, Baissac Y, Boutahar N, Adima AA, Kati-Coulibaly S, Jay-Allemand C (2011) Relationships between biochemical attributes (non-structural carbohydrates and phenolics) and natural durability against fungi in dry teak wood (*Tectona grandis* L.f.). Annals of Forest Science 68: 201-211

Nicholls JWP (1985) A new method for determining wood density in the standing tree. Australian Forest Research 15: 195-206

Nocetti M, Rozenberg P, Chaix G, Macchioni N (2011) Provenaces effect on the ring structure of teak (*Tectona grandis* L.f.) wood by X-ray microdensitometry. Annals of Forest Science 68: 1375-1383

Nugroho WD, Marsoem SN, Yasue K, Fujiwara T, Nakajima T, Hayakawa M, Nakaba S, Yamagishi Y, Jin HO, Kubo T, Funada R (2012) Radial variations in the anatomical characteristics and density of the wood of *Acacia mangium* of five different provenances in Indonesia. Journal of Wood Science 58: 185-194

Ogata K, Fujii T, Abe H, Bass P (2008) Identification of the timbers of Southeast Asia and the Western Pasific. Kaisheisha press, Ohtsu, pp 1-400

Palakit K, Siripattanadilok S, Duangsathaporn K (2012) False ring occurrences and their identification in teak (*Tectona grandis*) in North-Eastern Thailand. Journal of Tropical Forest Science 24: 387-398

Palanisamy K, Gireesan K, Nagarajan V, Hegde M (2009) Selection and clonal multiplication of superior trees of teak (*Tectona grandis*) and preliminary evaluation of clones. Journal of Tropical Forest Science 21: 168-174

Pande PK (2011) Variation in wood properties and growth in some clones of *Populus deltoides* Bartr. ex Marsh. American Journal of Plant Sciences 2: 644-649

Pande PK, Dhiman RC (2011) Performance and variability patterns in wood properties and growth traits in the parents, F_1 and F_2 generation hybrid clones of *Populus deltoides*. Journal of Forestry Research 22: 379-385

Panshin AJ, de Zeeuw C (1980) Textbook of wood technology: Structure, identification, properties, and uses of the commercial woods of the United States and Canada. Fourth edition. McGraw-Hill Book Company, New York, St. Louis, San Francisco, Auckland, Bogotá, Hamburg, Johannesburg, London, Madrid, Mexico, Montreal, New Delhi, Panama, Paris, São Paulo, Singapore, Sydney, Tokyo, Toronto, pp 1-722

Pedersen AP, Hansen JK, Mtika JM, Msangi TH (2007) Growth, stem quality and age-age correlations in a teak provenance trial in Tanzania. Silvae Genetica 56: 142-147

Pelletier MC, Henson M, Boyton S, Thomas D, Vanclay JK (2008) Genetic variation in shrinkage properties of *Eucalyptus pilularis* assessed using increment cores and test blocks. New Zealand Journal of Forestry Science 38: 194-210

Perum Perhutani (2000) Teak breeding and improvement in Perum Perhutani. In: Proceedings of third regional seminar on teak. Potentials and opportunities in marketing and trade of plantation teak: Challenge for the new millennium. Faculty of Forestry Universitas Gadjah Mada,Yogyakarta, pp: 215-220

Perum Perhutani (2012) Pemantapan proses bisnis menuju Perhutani ekselen. Annual Report. Perum Perhutani, Jakarta, pp 1-125 (in Indonesian)

Perum Perhutani (2014a) Wilayah kerja. http://perumperhutani.com/profil.wilayah-kerja/. Accessed on March 20, 2014 (in Indonesian)

Perum Perhutani (2014b) Jati plus Perhutani (JPP). http://perumperhutani.com/produk/bemih-dan-bibit/jati-plus-perhutani/. Accessed on April 21, 2014 (in Indonesian)

Poke FS, Potts BM, Vaillancourt RE, Raymond CA (2006) Genetic parameters for lignin, extractives and decay in *Eucalyptus globulus*. Annals of Forest Science 63: 813-821

Priya PB, Bhat KM (1998) False ring formation in teak (*Tectona grandis* L.f.) and the influence of environmental factors. Forest Ecology and Management 108: 215-222

Rao RV, Shashikala S (2005) Assessment of growth rate, basic density and heartwood content in selected teak clones of CSO, Thithimathi, Karnataka. In: Proceeding of the international conference on quality timber products of teak from sustainable forest management. Kerala Forest Research Institute, Peechi, pp 511-515

Raymond CA, MacDonald AC (1998) Where to shoot your Pilodyn: within tree variation in basic density in plantation *Eucalyptus globulus* and *E. nitens* in Tasmania. New Forests 15: 205-221

Roshetko JM, Rohadi D, Perdana A, Sabastian G, Nuryartono N, Pramono AA, Widyani N, Manalu P, Fauzi MA, Sumardamto P (2013) Teak systems' contribution to rural development in Indonesia. World Teak Conference 2013, Bangkok, Thailand. http://www.worldagroforestry.org/downloads/publications/PDFs/Pp13129.PDF. Accessed on April 22, 2014

Robertson RM, Reilly DF (2005) Performance of a 16-year-old stand of teak (*Tectona grandis* L.F.) in the Darwin area in relation to that in other trials in the Northern Territory. Information Booklet. Department of Primary Industry, Fisheries and Mines, Darwin, pp 1-12

Roda JM, Cadène P, Guizol P, Santoso L, Fauzan AU (2007) Atlas industri mebel kayu di Jepara, Indonesia. Center for International Forestry Research. Indonesia, Bogor, pp 1-54 (in Indonesian)

Ross RJ, McDonald KA, Green DW, Schad KC (1997) Relationship between log and lumber modulus of elasticity. Forest Products Journal 47 (2): 89-92

Rudman P, Da Costa EWB, Gay FJ (1967) Wood quality in plus trees of teak (*Tectona grandis* L.F.): An assessment of decay and termite resistance. Silvae Genetica 16: 102-105

Santos PET, Geraldi IO, Garcia JN (2004) Estimates of genetic parameters of wood traits for sawn timber production in *Eucalyptus grandis*. Genetics and Molecular Biology 27: 567-573

Simatupang MH (2000a) Some notes on the origin and establishment of teak forest (*Tectona grandis* L.F.) in Java, Indonesia. In: Proceedings of third regional seminar on teak. Potentials and opportunities in marketing and trade of plantation teak: Challenge for the new millennium. Faculty of Forestry, Gadjah Mada University, Yogyakarta, pp 91-98

Simatupang MH (2000b) Chemical properties of teakwood (*Tectona grandis* L.F.) as guide for selection of mother trees. In: Proceedings of third regional seminar on teak. Potentials and opportunities in marketing and trade of plantation teak: Challenge for the new millenium. Faculty of Forestry, Gadjah Mada University, Yogyakarta, pp 255-264

Siswamartana S (1998) Teak forest management in Indoenesia. http://www.fao.org/dorcep/005/AC773E/ac773e0d.htm. Accessed on April 23, 2014

Siswamartana S (2005) Ups and downs of teak forest management in Indonesia. In: Proceeding of the international conference on quality timber products of teak from sustainable forest management. Quality timber products of teak from sustainable forest management. Kerala Forest Research Institute, Peechi, pp 63-67

Soerianegara I, Lemmens RHMJ (1994) Plant resources of South-East Asia 5, (1) Timber trees: Major commercial timbers. Prosea, Bogor, pp 1-610

Solorzano S, Moya R, Murillo O (2012) Early prediction of basic density, shrinking, presence of growth stress, and dynamic elastic modulus based on the morphological tree parameters of *Tectona grandis*. Journal of Wood Science 58: 290-299

Sprague JR, Talbert JT, Jett JB, Bryant RL (1983) Utility of the Pilodyn in selection for mature wood specific gravity in loblolly pine. Forest Science 29: 696-701

Suhaendi H (1998) Teak improvement in Indonesia. http://www.fao.org/DORCEP/005/AC773e /ac773e0c.htm. Accessed on May 24, 2012

Sumarna Y (2011) Kayu Jati: Panduan budi daya dan prospek bisnis. Penebar Swadaya. Jakarta, pp 1-91 (in Indonesian)

Susanto M, Prayitno TA, Fujisawa Y (2008) Wood genetic variation of *Acacia auriculiformis* at Wonogiri trial in Indonesia. Journal of Forestry Research 5: 135-145

Suseno OH (2000) The history of teak silviculture in Indonesia. In: Proceedings of third regional seminar on teak. Potentials and opportunities in marketing and trade of plantation teak: Challenge for the new millenium. Yogyakarta, Indonesia, pp 177-184

Swain D, Mandal AK, Sharma R (1999) Genetic analysis in teak (*Tectona grandis*). Journal of Tropical Forest Science 11: 582-586

Taylor FW (1981) Rapid determination of southern pine specific gravity with a Pilodyn tester. Forest Science 27: 59-61

Thulasidas PK, Bhat KM (2007) Chemical extractive compounds determining the brown-rot decay resistance of teak wood. Holz als Roh- und Werkstoff 65: 121-124

Thulasidas PK, Bhat KM (2012) Mechanical properties and wood structure characteristics of 35-year old home-garden teak from wet and dry localities of Kerala, India in comparison with plantation teak. Journal of the Indian Academy of Wood Science 9: 23-32

Thulasidas PK, Bhat KM, Okuyama T (2006) Heartwood colour variation in home garden teak (*Tectona grandis*) from wet and dry localities of Kerala, India. Journal of Tropical Forest Science 18: 51-54

Vanclay JK, Henson M, Palmer G (2008) Color variation and correlations in *Eucalyptus dunnii* sawnwood. Journal of Wood Science 54: 431-435

Veenin T, Fujita M, Nobuchi T, Siripatanadilok S (2005) Radial variations of anatomical characteristics and specific gravity in *Eucalyptus camaldulensis* clones. IAWA Journal 26: 353-361

Wang X, Ross RJ, McClellan M, Barbour RJ, Erickson JR, Forsman JW, McGinnis GD (2001) Nondestructive evaluation of standing trees with a stress wave method. Wood and Fiber Science 33: 522-533

Wang X, Ross RJ, McClellan M, Barbour RJ, Erickson JR, Forsman JW, McGinnis GD (2000) Strength and stiffness assessment of standing trees using a non destructive stress wave technique. Research Paper FPL-RP-585. United States Department of Agriculture, Madison, pp 1-9

Wei X, Borralho NMG (1997) Genetic control of wood basic density and bark thickness and their relationships with growth traits of *Eucalyptus urophylla* in South East China. Silvae Genetica 46: 245-250

White TL, Adams WT, Neale DB (2007) Forest genetics. CAB International, Cambridge, pp 1-682

Windeisen E, Klassen A, Wegener G (2003) On the chemical characterisation of plantation teakwood from Panama. Holz als Roh- und Werkstoff 61: 416-418

Woods JH, Kolotelo D, Yanchuk AD (1995) Early selection of coastal Douglas-fir in a farm-field test environment. Silvae Genetica 44: 178-186

Wu SJ, Xu JM, Li GY, Risto V, Lu ZH, Li BQ, Wang W (2010) Use of the Pilodyn for assessing wood properties in standing trees of *Eucalyptus* clones. Journal of

Forestry Research 21: 68-72

Wu SJ, Xu JM, Li GY, Risto V, Lu ZH, Li BQ, Wang W (2011) Estimation on basic density and modulus of elasticity of eucalypt clones in Southern China using non-destructive methods. Journal of Tropical Forest Science 23: 51-56

Yamamoto K, Hong LT (1989) Location of extractives and decay resistance in some Malaysian hardwood species. Journal of Tropical Forest Science 2: 61-70

Yamamoto K, Simatupang MH, Hashim R (1998) Caoutchouc in teak wood (*Tectona grandis* L.f.): formation, location, influence on sunlight irradiation, hydrophobicity and decay resistance. Holz als Roh- und Werkstoff 56: 201-209

Yanchuk AD, Spilda I, Micko MM (1988) Genetic variation of extractives in the wood of trembling aspen. Wood Science and Technology 22: 67-61

Zobel BJ, Jett JB (1995) Genetics of wood production. Springer-Verlag, Berlin, Heidelberg, New York, London, Paris, Tokyo, Hong Kong, Barcelona, Budapest, pp 1-337

Zobel BJ, van Buijtenen JP (1989) Wood variation its causes and control. Springer-Verlag, Berlin, Heidelberg, New York, London, Paris, Tokyo, pp 1-363

Studies on variation of wood properties in plantation-grown teak (*Tectona grandis* L.f.) in Indonesia

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Summary

Chapter 1 Introduction

Teak (*Tectona grandis* L.f.) is an important commercial plantation species in Indonesia, due to its high valuable timber. In recent decades, the demand for teak wood is increasing in Indonesia. However, the demands are exceeding the supply of the teak wood. Thus, tree breeding programs have been developed to produce more productive teak forest in Indonesia, such as establishment of clonal test sites and seed provenance test sites. However, tree breeding programs in Indonesia still only focuse on growth characteristics and durability characteristics, such as stem diameter, tree height, stem form, branching, and resistance to pest and disease. It is, therefore, essential to evaluate the wood property of breeding materials. The objectives of this study are to evaluate the growth characteristics and wood properties of teak breeding materials selected by growth characteristics through the teak breeding programs in Indonesia.

Chapter 2 Growth characteristics, stress-wave velocity, and Pilodyn penetration of 15 clones from 12-year-old teak trees planted at two different sites in Indonesia

Growth characteristics [stem diameter (*D*), tree height (TH), and bole volume (*V*)], stress-wave velocity (SWV), and Pilodyn penetration (*P*) were measured for 15 clones of 12-year-old teak trees planted at two different sites in Indonesia. Based on the obtained data, the following items were clarified: the variations in tree growth characteristics, SWV, and *P* among clones, their repeatability (*R*), interactions

between genotype and environment, and correlations between measured characteristics.

The mean values for *D*, TH, *V*, SWV, and *P* of the 15 teak clones planted in Cepu ranged 11.3 – 25.2 cm, 7.7 – 15.7 m, 0.136 – 0.658 m^3, 3.37 – 3.78 km/s, and 18.7 – 27.6 mm, respectively. The mean values of these characteristics of teak clones planted in Ciamis ranged 17.0 – 37.7 cm, 12.3 – 23.7 m, 0.295 – 1.472 m^3, 3.23 – 3.77 km/s, and 21.0 – 26.9 mm, respectively. Significant differences of all measured characteristics were found among 15 clones at both sites. Their *R* showed relatively moderate to high values in both of sites. The *R* values of *D*, TH, *V*, SWV, and *P* in 15 clones of 12-year-old teak trees planted at Cepu and Ciamis in Indonesia were 0.50 and 0.76, 0.39 and 0.44, 0.51 and 0.77, 0.30 and,0.27, and 0.60 and 0.65, respectively. These results indicate that these characteristics are closely related to genetic factors. Significant interactions between genotype and environment were found in all measured characteristics, suggesting that interactions between genotype and environment should be considered when the teak plantations are established in Indonesia. In addition, SWV and *P* showed lower interactions between genotype and environment than growth characteristics.

Highly positive significant correlations were found among growth characteristics (*D*, TH, and *V*). These results indicate that growth characteristics are closely related each other in teak clones. Thus, *D* is one of suitable criteria in tree breeding programs of teak for selecting plus trees with radial growth and height growth, and high bole volume. On the other hand, no significant correlations were found between growth characteristics and SWV, suggesting that SWV is independent of growth characteristics in teak trees. Based on these results, wood properties and growth characteristics of teak trees are considered to be improved by tree breeding programs.

Chapter 3 Variation in tree growth characteristics, stress-wave velocity, and Pilodyn penetration of 24-year-old teak trees originating from 21 seed provenances planted in Indonesia

The variation of growth characteristics (*D*, TH and *V*), SWV, and *P* among seed provenances were characterized for 21 seed provenances of 24-year-old teak trees planted in Indonesia. In addition, *R* and correlations between the measured characteristics were also determined.

The mean values of *D*, TH, *V*, SWV, and *P* in each seed provenance ranged 14.8 – 31.5 cm, 12.8 – 21.8 m, 0.228 – 1.126 m^3, 3.02 – 3.39 km/s, and 20.4 – 25.9 mm, respectively. Significant differences among provenances were observed for all measured characteristics, indicating that these characteristics are genetically controlled. The *R* of growth characteristics, SWV, and *P* were moderate values. The *R* values of *D*, TH, *V*, SWV, and *P* were 0.27, 0.27, 0.20, 0.24, and 0.23, respectively. These results indicate the potentials for improving growth characteristics and wood properties of teak trees with the help of breeding programs. Highly significant positive correlations were observed among the growth characteristics, suggesting that they are closely related. In contrast, no significant correlations were observed between the growth characteristics and SWV, indicating that they are independent. It is concluded that mechanical properties are also important criteria for selecting plus trees in tree breeding programs. Principal component analysis revealed that seed provenances from Indonesia (Bangilan, Deling, and Randublatung) and India (Malabar and Central Province) showed high scores of both growth characteristics and SWV, suggesting their canditate sources for establishing teak plantation.

Chapter 4 Among-clone variations of anatomical characteristics and wood properties in teak planted in Indonesia

The anatomical characteristics [vessel diameter (VD), fiber wall thickness (FWT), fiber diameter (FD), vessel element length (VEL), and fiber length (FL)] and wood properties [basic density (BD) and compressive strength parallel to grain (CS) at the green condition] were investigated for 27 trees from nine teak clones planted in Indonesia.

The mean values of VD, FWT, FD, VEL, FL, BD, and CS were 188 μm, 2.78 μm, 23.4 μm, 0.284 mm, 1.42 mm, 0.51 g/cm^3, and 37.5 MPa, respectively. Clone P showed the lowest values of VD, FD, and VEL, whereas the highest values of FWT, BD, and CS. Significant differences among the nine clones were found in VEL, BD, and CS. Moderate to high values of *R* were obtained for FD, VEL, BD, and CS. The *R* values of FD, VEL, BD, and CS were 0.22, 0.36, 0.39, and 0.60, respectively. These results indicate that these characteristics are genetically controlled. In addition, a significant positive correlation was found between BD and FWT, indicating that

FWT is strongly correlated with BD in teak.

Radial variations of VD, FWT, VEL, and FL gradually increased from pith to bark. FD slightly increased near the pith and then became almost constant outward. Radial variation of BD also showed a gradual increase from pith to bark. On the other hand, radial variation of CS varied rather considerbly and slightly increased from pith to bark. Thus, the trends of radial variations of the anatomical characteristics and wood properties were similar for all clones. Furthermore, radial variation of FL with respect to relative distance from the pith showed almost the same pattern for the two radial growth rate categories. This result suggests that xylem maturation depends on cambial age rather than radial growth in teak trees. It is, therefore, concluded that after formation of mature wood, intensive silvicultural practices should be applied to produce as much mature wood as possible in teak plantations.

Chapter 5 Variation of decay resistance, heartwood color, and extractive contents in 12-year-old teak clones planted in Indonesia

The variations of decay resistance, heartwood color, and extractive contents among clones were clarified. Furthermore, the relationships between mass loss and other characteristics were also clarified for the total 26 trees from nine clones of 12-year-old teak trees planted in Indonesia.

The mean value of mass loss, *L**, *b**, *a**, ethanol-toluene extract contents, tectoquinone, palmitic acid, lapachol, 2-(hydroxymethyl)anthraquinone, and squalene of 26 sample trees from nine clones were 24.7%, 61.9, 5.6, 17.9, 6.8%, 5.65 μmol/g, 0.13 μmol/g, 0.78 μmol/g, 1.69 μmol/g, and 1.84 μmol/g, respectively. Significant differences among clones were found in decay resistance (mass loss) and heartwood color (*L** and *a** values). The *R* values of mass loss, *L**, and *b** were 0.55, 0.64, and 0.42, respectively. Moderate to high values of *R* for these characteristics suggest that these characteristics are genetically controlled in teak trees. Furthermore, no significant differences were found in *b** values of heartwood and extractive contents. In addition, low to moderate values of *R* were found in extractive contents. The *R* values of ethanol-toluene extract, tectoquinone, palmitic acid, lapachol, 2-(hydroxymethyl)anthraquinone, and squalene were 0.26, 0.01, 0.23, 0.26, 0.08, and 0.25, respectively. Furthermore, significantly negative correlation was found between mass loss and 2-(hydroxymethyl)anthraquinone content, suggesting that this compound is related to decay resistance of teak. Based on these results, therefore, decay resistance, heartwood color, and 2-(hydroxymethyl)anthraquinone content are important factors to improve the wood durability in teak breeding programs.

Chapter 6 Conclusion

The growth characteristics and wood properties varied among clones and seed provenances. These considerable variations in different growth characteristics and wood properties among clones and seed provenances show the opportunities to improve the wood properties and growth characteristics of teak trees by application of an appropriate tree breeding program. The results in this study suggest that using a selection index integrating more than a single property will be effective rather than a single property in teak trees. In addition, to produce more mature teak wood, intensive silvicultural practices should be applied after forming mature wood in the teak plantation. Furthermore, it is suggested that the use of better planting material (from breeding programs) combined with proper intensive silvicultural practice will produce more trees with good growth characteristics, good wood quality, and younger rotation age (more productive teak forest).

インドネシアにおけるチーク（*Tectona grandis* L.f.）植林木の木材性質の変異に関する研究

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ファニー ヒダヤティ

第 1 章　緒言

チーク（*Tectona grandis* L.f.）は，その材が高値で商取引されるため，インドネシアにおいて重要な産業植林樹種の一つである．近年，インドネシアにおけるチーク材の需要は，増加傾向にあるが，その需要量は供給量を上回っており，需給の不均衡が生じている．この問題の解決のため，インドネシアにおいては，より生産力のあるチーク林を造成することを目的として，林木育種計画においてクローン試験地および種子産地試験地が設定されてきた．これまでに，インドネシアにおける林木育種計画では，成長形質（幹直径，樹高，樹形および分枝性）および病害抵抗性などが特に着目されてきた．そのため，これら育種母材の木材性質を評価した例はほとんどない．従って，育種母材の木材性質を評価することは必須である．本研究では，インドネシアにおけるチークの林木育種計画を通じて，成長形質によって選抜されたチーク育種母材の成長形質および木材性質を評価することを目的とした．

第 2 章　インドネシアの異なる 2 立地に植栽された 12 年生チーク 15 クローンにおける成長特性，応力波伝播速度およびピロディン打込み深さ

成長特性，応力波伝播速度（SWV）およびピロディン打込み深さ（*P*）のクローン間変異，反復率，遺伝型と環境の交互作用および測定した形質間の相関関係を解明するために，異なる 2 立地（Cepu および Ciamis）に植栽された 12 年生チーク 15 クローンについて，成長特性［幹直径（*D*），樹高（TH）および幹材積（*V*）］，SWV および *P* を調査した．

Cepu に植栽されたチーク 15 クローンにおける，*D*，*H*，*V*，SWV および *P* の平均値は，それぞれ 11.3～25.2 cm，7.7～15.7 m，0.136～0.658 m^3，3.37～3.78 km/s および 18.7～27.6 mm であった．一方，Ciamis に植栽されたクローンにおける，これらの平均値は，それぞれ 17.0～37.7 cm，12.3～23.7 m，0.295

〜1.472 m^3，3.23〜3.77 km/s および 21.0〜26.9 mm であった．すべての測定した形質について，両立地ともに 15 クローン間に有意差が認められた．両立地における *D*，TH，*V*，SWV および *P* の反復率は，それぞれ 0.50 と 0.76，0.39 と 0.44，0.51 と 0.77，0.30 と 0.27 および 0.60 と 0.65 であり，中庸から高い値を示した．これらの結果は，本研究で測定した形質が，遺伝因子と密接に関係していることを示している．また，測定したすべての形質において，遺伝型と環境の間に有意な交互作用が認められた．このことから，インドネシアでチーク人工林を造成する際に，遺伝型と環境の交互作用を考慮しなければならないことが明らかとなった．さらに，SWV および *P* における遺伝型と環境の交互作用は，成長形質と比較して，より低い傾向を示した．

測定した形質間の相関関係を調査した結果，成長形質（*D*，TH および *V*）の間で，有意な高い正の相関関係が認められた．このことから，チーククローンにおいて，成長形質は，互いに密接に関系していることが明らかになった．従って，チークの林木育種計画において，良好な肥大および樹高成長そして高い幹材積を持つ精英樹を選抜するために，*D* は優れた評価基準の一つであると考えられる．一方，成長形質と SWV との間に，有意な相関関係は認められず，チークにおいて，SWV は成長形質とは独立していることが示唆された．以上の結果より，チークにおける木材性質および成長形質は，林木育種計画によって改良可能であると考えられる．

第 3 章　インドネシアに植栽された 21 種子産地由来の 24 年生チークにおける成長特性，応力波伝播速度およびピロディン打込み深さの変異

本章では，インドネシアに植栽された 21 種子産地由来の 24 年生チークにおける，成長形質（*D*，TH，*V*），SWV および *P* の産地間変異を調査した．また，反復率および測定した形質間の相関関係も考察した．

21 種子産地の *D*，TH，*V*，SWV および *P* の平均値の最小値と最大値は，それぞれ 14.8〜31.5 cm，12.8〜21.8 m，0.228〜1.126 m^3，3.02〜3.39 km/s および 20.4〜25.9 mm であった．全ての測定した形質について，産地間で有意差が認められた．このことから，これらの形質は，遺伝的に影響を強く受ける事が明らかとなった．また，*D*，TH，*V*，SWV および *P* の反復率は，それぞれ 0.27，0.27，0.20，0.24 および 0.23 であり，いずれも中庸な値であった．さらに，成長形質間に，有意な高い正の相関関係が認められた．このことか

ら，成長形質が互いに密接に関係していることが明らかとなった．一方，成長形質と SWV との間に有意な相関関係は認められず, これらは独立していることが示唆された．このことから，チーク林木育種計画における精英樹選抜において, ヤング率などの機械的性質も重要な評価基準であると考えられる．また，主成分分析を行った結果，インドネシア（Banglian，Deling および Randublatung）およびインド（Malabar および Central Province）由来の種子産地が, 成長形質および SWV 両方において高い主成分得点を持つことを示した．従って，これらの種子が，インドネシアのチーク造林地の確立のために，有望な供給源となる可能性がある．

第 4 章　インドネシアに植栽されたチークにおける組織学的特徴および木材性質のクローン間変異

インドネシアに植栽された，チーク 9 クローン 27 個体について，組織学的特徴［道管直径（VD），木繊維壁厚（FWT），木繊維直径（FD），道管要素長（VEL）および木繊維長（FL）］および木材性質［容積密度（BD），生材状態の縦圧縮強さ（CS）］を調査した．

VD，FWT，FD，VEL，FL，BD および CS の平均値は，それぞれ 188 μm，2.78 μm，23.4 μm，0.284 mm，1.42 mm，0.51 g/cm^3 および 37.5 MPa であった．Clone P は，VD，FD および VEL について最小値を示し，一方，FWT，BD および CS については，最大値を示した．VEL，BD および CS について，9 クローン間で有意差が認められた．FD，VEL，BD および CS の反復率は，それぞれ 0.22，0.36，0.39 および 0.60 であり，中庸から高い値を示した．これらの結果は，組織学的性質と木材性質においても遺伝的影響が強いことを示唆している．さらに，BD と FWT との間に，有意な正の相関関係が認められたことから，チークにおいて，BD の大小は FWT に大きく影響を受けると考えられる．

VD，FWT，VEL および FL は，髄から樹皮側に向かって緩やかに増加する傾向を示した．一方，FD は，髄付近でわずかに増加し，外側に向かってほぼ一定となる傾向が認められた．BD では，髄から樹皮側に向かって緩やかに増加する傾向を示した．また，CS は，半径方向で値が変動するものの，髄から樹皮側に向かってわずかに増加する傾向を示すことが明らかとなった．さらに，組織学的特徴および木材性質の半径方向変動パターンは，すべてのクロ

ーンにおいて類似していた．一方，髄からの相対距離に基づくFLの半径方向変動は，2 つの肥大成長区分においてほぼ同様のパターンを示した．このことは，チークにおける材成熟は，肥大成長よりもむしろ形成層齢に依存していることを示唆している．従って，チークにおいて，できるだけ多くの成熟材を生産するためには，成熟材形成後の集約的な施業が重要であると考えられる．

第5章　インドネシアに植栽された12年生チークにおける耐朽性，心材色および抽出成分量のクローン間変異

インドネシアに植栽された12年生チーク9クローン26個体について，耐朽性，心材色および抽出成分量のクローン間変異を調査した．また，得られた結果より，腐朽による質量減少率とその他の形質との関係を明らかにした．

9クローン26個体における，質量減少率，心材色（*L**，*b**および*a**），エタノール–トルエン抽出物量，テクトキノン，パルミチン酸，ラパコール，2–（ヒドロキシメチル）アントラキノンおよびスクワレン量の平均値は，それぞれ24.7%，61.9，5.6，17.9，6.8%，5.65 µmol/g，0.13 µmol/g，0.78 µmol/g，1.69 µmol/gおよび1.84 µmol/gであった．腐朽による質量減少率および心材色（*L**および*a**値）において，クローン間に有意差が認められた．腐朽による質量減少率および*L**および*a**における反復率は，それぞれ0.55，0.64および0.42 であり，中庸から高い値を示した．従って，チークにおけるこれらの形質は，遺伝的に制御されていることが示唆された．一方，心材の*b**値および抽出成分量については，クローン間に有意差が認められなかった．また，抽出物量および各抽出成分量において，中庸から低い値の反復率が得られた．エタノール–トルエン抽出物量，テクトキノン，パルミチン酸，ラパコール，2–（ヒドロキシメチル）アントラキノンおよびスクワレン量における反復率は，それぞれ0.26，0.01，0.23，0.26，0.08および0.25であった．さらに，腐朽による質量減少率と2–（ヒドロキシメチル）アントラキノン量との間に有意な負の相関が認められた．このことから，2–（ヒドロキシメチル）アントラキノンがチーク材の耐朽性に関与していることが示唆された．以上の結果より，チーク林木育種計画において，耐朽性，心材色および2–（ヒドロキシメチル）アントラキノン量は重要な形質であると考えられる．

第 6 章　結論

本研究では，インドネシアに植栽されたチークの成長形質および木材性質について，クローン間および種子産地間変異を明らかにした．成長形質および木材性質におけるクローン間および種子産地間変異は，適切な林木育種計画の適用による，チークの木材性質および成長形質に関する改良の可能性を示唆している．また，チークにおいては，単一の形質のみで優良個体を選抜するよりも，成長形質と木材性質といった複数の形質により優良個体を選抜する重要性が明らかとなった．さらに，より多くの成熟材を持つチーク材を生産するために，成熟材を形成する樹齢以降の人工林において，集約的な施業が重要であることが明らかとなった．本研究で得られた結果から，適切で集約的な施業と組み合わせて，より良質な苗木（育種母材由来）を使用した場合，伐期を短縮し，良好な成長形質および良質な木材性質を持つ，より均質なチーク材の生産が可能であると考えられる．