Effect of growth rate on wood quality of teak (*Tectona grandis* Linn.f.) grown under differing site quality conditions.

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THESIS

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2013

DECLARATION

I hereby declare that this thesis entitled "**Effect of growth rate on wood quality of teak (*Tectona grandis* Linn.f.) grown under differing site quality conditions.**" is a bonafide record of research done by me during the course of research and that the thesis has not previously formed the basis for the award of any degree, diploma, fellowship or other similar title, of any other University or Society.

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CERTIFICATE

Certified that this thesis, entitled **"Effect of growth rate on wood quality of teak (*Tectona grandis* Linn.f.) grown under differing site quality conditions."** is a record of research work done independently by **Mr. Anish, M.C. (2011-17-104)** under my guidance and supervision and it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to him.

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ANISH, M.C

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INTRODUCTION

INTRODUCTION

Teak (*Tectona grandis* L.f.) is the most important hardwood species of the world (FAO, 2013). It is highly priced by the wood industry due to its superior mechanical and physical properties, as well as its pleasing aesthetic appearance (Sanwo, 1987, 1990; Kjaer et al., 1999). It occurs naturally in India, Myanmar, Thailand and Laos whereas it is naturalized in Java provenance / regions of Indonesia, where it was probably introduced some 400 to 600 years ago. Natural teak forests are estimated to cover 29.035 million ha in India.

Teak is a small proportion of world timber production and trade. The estimated market share of teak logs in total round wood production is less than two per cent, but in terms of value it is much larger since teak is part of the high-value hardwood in the market, and is a major component of the forest economies of many tropical countries. Globally they constitute the only planted hardwood resource that is increasing in terms of area (Kollert and Cherubini, 2012).

Globally, teak plantations constitute about 8 percent of the total plantation area (Pandey and Brown, 2000). Even if the amount of tropical hardwood plantations in the world increased significantly within a few years, it would only be able to supply a very small percentage of the world demand (WGF, 2011). Massive plantation programmes, mainly in the private sector were started in India and elsewhere in the past two decades to maximise timber productivity and through genetic selection and intensive silvicultural techniques that accelerate tree growth for early harvesting (Bhat and Indira, 1997). Then the age old question arises, whether the faster grown wood is of inferior quality as compared to that of trees grown under the normal conditions of natural forests / plantations.

The topic, "quality of quickly grown teak" was not a new one. It has been debated as early as 1895, when Bourdillon (1895) and Lushington (1895) supported the argument that, faster-grown timber is inferior. But at the same time John Lindley, the contemporary authority in silviculture tried to prove the superiority of faster-grown timber. Even though results of past studies were of limited use and even conflicting, there still exists a general belief that, faster growth rate results in the production of wood of inferior quality (Chowdhury, 1952; Bryce, 1966).

The three important factors which influence the faster growth rate of timber species are: genetics, site factors and management practices. Since timber quality depends on tree form, wood structure and strength properties, it is likely to be affected by the quick growth of teak. Therefore, quick growth rate can influence on the physical, anatomical, biochemical and mechanical properties of wood. Specific gravity which has a strong relationship with strength properties is taken as the major indicator of quality of teak wood (Jayawardana and Amarasekera, 2009). Bhat et al. (1987) indicated an increase of 14 percent in wood density for faster grown dominant trees than suppressed trees in the same stand. Some studies supported the result that wood basic density and strength properties were higher for fast grown ring porous wood (Nair and Mukherji, 1957; Harris, 1981). Wheeler (1987) also reported a positive correlation between growth rate and wood density for temperate ring porous species. Apart from wood specific gravity, percentage of heartwood content (Okuyama et al., 2000) had also been used as a good indicator of the quality of teak wood. Studies have been done on the heartwood proportion / heartwood sapwood ratio and heartwood distribution in relation to teak growth. A study on characterisation of juvenile wood in teak showed that the vessel diameter/percentage in teak wood can also been considered as one of the best anatomical indicators of age demarcation between juvenile and mature wood, although maturation age varies depending on different anatomical properties (Bhat et al., 2001).

Therefore, observations on physical parameters (variations in bark thickness, heartwood colour, moisture content etc.), anatomical parameters (vessel morphology, ray morphology etc.) and biochemical parameters (extractive content analysis) were of high importance in wood quality studies since these were considered as good indicators of wood quality. Ring width, since it reflects the radial growth of a tree resulting from the activity of vascular cambium is considered as one of the major indicators of growth rate (Zobel and van Buijtenen, 1989).

The objectives of the present study are (1) analyse the effect of rate of growth on the wood quality of teak with special reference to the samples collected from important teak growing regions within the country as well as from outside. (2) analyse the variation in wood physical, anatomical and biochemical properties between the provenance / geographic sources in the above two categories.

REVIEW OF LITERATURE

REVIEW OF LITERATURE

Teak (*Tectona grandis* L.f.) is a large, deciduous or semi-deciduous tree depending on climate seasonality, growing in a wide range of climatic and edaphic conditions *e.g.* mean annual temperature 14-36° C and annual rainfall 600-4000 mm, but preferring contrasting dry and wet seasons (Orwa et al., 2009). It is one of the most important tree species in tropical regions and probably the most highly-valued hardwood due to its quality, attractiveness and durability (Bishop, 1999).

2.1 Global overview of teak plantations

Teak (*Tectona grandis*) is one of the world's premier hardwood timbers, rightly famous for its mellow colour, fine grain and durability. It occurs naturally only in India, Myanmar, the Lao People's Democratic Republic and Thailand, and it is naturalized in Java regions of Indonesia, where it was probably introduced some 400 to 600 years ago (Troup, 1921; Kadambi, 1972; White, 1991; Pandey and Brown, 2000; Bhat and Ok Ma, 2004). Teak has been established throughout Asia as well as introduced into many tropical countries, *e.g.* Togo (Kokutse et al., 2004), Kenya (Jacoby, 1989), Nigeria (Akachuku and Abolarin, 1989), Costa Rica (Bermejo et al., 2004), Brazil (Nogueira et al., 2006), Panama (Posch et al., 2004), Venezuela (Kammesheidt, 2001) and Australia (Robertson and Reilly, 2004), and also in some islands in the Pacific regions (Papua New Guinea, Fiji and the Solomon Islands) (Pandey and Brown, 2000).

Teak was introduced to countries of tropical Africa to supplement local timber supplies because of its excellent timber properties. Early introductions of teak outside Asia were made in Nigeria, where the first introductions were of Indian origin in 1902 (Horne, 1966) and subsequently were of Burmese origin. Teak planting in eastern Ghana started around 1905 and a small plantation of teak was established in the Ivory Coast in 1929 (Kadambi, 1972).

The first pure teak plantation in Tropical America was established in Trinidad in 1913 (Keogh, 1979) with seed from Burma. Planting of teak in Honduras, Panama and Costa Rica started between 1927 and 1929 (Ball et al., 1999).

Reliable area statistics on the historical progress made in teak plantation are incomplete, but it appears that the major area under teak plantation, of about 0.31 million ha, was in Java (Indonesia) until 1950. It was estimated that the teak plantations in the tropical countries gradually increased during the 1950s and 1960s until the reported plantation area of teak by 1970 was estimated as 0.891 million ha (Kadambi, 1972; Tewari, 1992). The pace of planting teak further accelerated in the late 1970s with the financial support provided by external donor agencies. The total area of teak plantations reported by 38 countries is estimated to be 4.346 million ha, of which 83 percent Nilambur (Ribbenthrop, 1900). It is cultivated throughout the tropics in varying extent. The area of planted teak forest reported by 38 countries was estimated to be 4.346 million was in Asia, 11 percent in Africa and 6 percent in tropical America (Kollert and Cherubini, 2012).

2.2 Teak planting - the Indian Perspective

Teak is known to exhibit wide geographic/ provenance variations in India with regard to wood figure and strength properties (Chundamannil, 1998). For the first time, teak plantations were raised in India in 1842 in ha. Extensive teak plantations exist in India outside the zones of its natural distribution. As on teak plantations in India covers 1.67 million ha (i.e. 38 percent of the total) (Kollert and Cherubini, 2012). The Malabar teak (Nilambur, Kerala) from the Western Ghat region in India, generally displaying good growth and log dimensions with desired wood figure and golden yellowish brown colour, has a wide reputation in the world trade for ship-building. The central Indian teak from the drier region is reputed for better tree form, deeper colour and twisted or wavy grain, although it is stated to be often 7–8% lighter than South Indian and Myanmar teak (Bhat and

Priya, 2004). However, Nicodemus et al. (2005) reported greater genetic diversity in the teak populations of the Western Ghats region than in Central India.

Teak varies greatly from locality to locality in timber characteristics such as colour, grain, texture and figure (Bedell, 1989). Without considering provenance as a source of variation, earlier studies reported contradictory findings with regard to the relationship between growth rate and wood properties in teak (Bourdillon, 1895; Chowdhury, 1952; Mukherji and Bhattacharya, 1963; Bryce, 1966; Rao et al., 1966; Bhat, 1998; Bhat and Priya, 2004). The availability of information on the genetic variation within population and the differentiation between populations plays a significant role in the formation of appropriate management strategies for conservation of genetic resources (Milligan et al., 1994). Narayanan et al. (2007) analysed the molecular diversity and identity of Indian teak plus trees using RAPD and ISSR markers. Recently, Ansari et al. (2012) applied the technology of ISSR markers for the estimation of genetic diversity of teak populations belonging to its entire natural range in India.

Another important field of teak research in India is on dendrochronology. The science of reconstructing past climate by use of tree-rings is known as dendroclimatology which is a branch of the more general discipline of dendrochronology (Fritts, 1976). Since *T. grandis* is one of the tropical species that shows clear growth rings and suitable for climatic analysis (Chowdhury, 1964; Détienne, 1989; Bhattacharyya and Shah, 2009), so it is widely used in the dendrochronological studies in the tropics.

2.3 Rate of growth

There is a general agreement in the literature that teak growth varies between locations (Priya and Bhat, 1997) but most of the available studies come from Asian countries, especially India (Ram et al., 2008, 2010). Tree ring width is one of the most important variables for studying tree growth (Tian et al., 2009), and growth rate helps to clarify forest dynamics, an important factor in the sustainable management of forest resources (Fritts, 1976; Jacoby, 1989; Priya and Bhat, 1997; Pant, 2003). Ring width is also considered a good anatomical indicator of age (Priya and Bhat, 1998; Bhat et al., 2001), and *T. grandis* is one of the tropical species that shows clear growth rings and suitable for climatic analysis (Chowdhury, 1964; Détienne, 1989; Bhattacharyya and Shah, 2009), so it is widely used in dendrochronological studies in the tropics.

Radial growth depends on a combination of climate and local environmental factors including soil type, light availability and competition from neighbours. Annual ring width across a wide range of tree species has been found to be correlated with climatic data from several specific months in either the preceding or the current year's growth of a tree (Fritts, 1976; Brienen and Zuidema, 2005; Devall and Parresol, 2005; Trouet et al., 2006).

Teak radial growth has also been found to be correlated with monthly precipitation (Murphy, 1994; Pumijumnong et al., 1995 and Shah et al., 2007 as well as monthly temperature (Devall and Parresol, 2005). Piutti and Cescatti (1997) have carried out studies in temperate species on the interaction between climatic response and within species competition on radial growth, but in large-leaved trees such as teak, very limited information exists. Dominant teaks possess crowns high in the canopy and thus may be susceptible to high temperatures resulting in increased evapotranspiration, which would in turn be reflected in radial growth. Radial growth depending on the growing environment of individuals has been examined in temperate timber species (Eckstein et al., 1989; Bert and Danjon, 2006) but little information exists concerning tropical species (Sahri et al., 1998a; Morataya et al., 1999; Wadsworth et al., 2003). If the influence of provenance on radial growth and wood quality in teak was better understood, it would be possible to manipulate such characteristics, taking into account the growing environment of trees within a plantation (Sahri et al., 1998b; Morataya et al., 1999).

2.4 Ring width analysis

Tropical tree-ring studies have been increasingly pursued over the past, and with increasingly greater success (Pumijumnong et al., 1995; D' Arrigo et al., 1994, 1997, 2006; Buckley et al., 1995, 2001, 2005, 2007). Much of the interest is driven by the need to understand the role of tropics in our changing global climate, where tree-rings can be used as one proxy source of terrestrial climate. Tree-ring chronologies have been developed and used by many tree-ring scientists to reconstruct relatively local temperature and precipitation histories at various locations in India (Pant and Borgaonkar., 1984; Borgaonkar et al., 1994, 1996; Bhattacharyya and Yadav, 1999; Singh et al., 2009). The use of dendrochronology to study growth ring width in trees has shown that it is possible to successfully date many tropical species in West Africa, and the occurrence of annual rings has been demonstrated in teak in Thailand (Pumijumnong et al., 1995), India (Priya and Bhat, 1998; Shah et al., 2007) and Central America (Devall and Parresol, 2005).

Teak has been widely analysed and is suitable for environment and climatic analysis (Bhattacharyya et al., 1992; Pumijumnong et al., 1995; Yadav and Bhattacharyya, 1996; Shah et al., 2007; Managave et al., 2010). Ram et al. (2008; 2010) demonstrated the influence of moisture on the annual growth rate of teak in Central India through the analysis of tree ring width. Chowdhury (1940) recorded the variation in periodicity of cambium in relation to growth-ring formation in teak growing in Dehradun, Chittagong and Nilambur of the Indian subcontinent and also Priya and Bhat (1997; 1998) reported anatomical changes in juvenile wood following insect defoliation and the influence of environmental factors on the formation of false rings in teak growing in the southern part of India.

After Chowdhury's initial work on growth ring formation in relation to climate, many works has been carried out in teak from the point of view of dendroclimatology at several sites in India viz., from moist deciduous forests in Thane, Maharashtra (Pant and Borgaonkar,1983; Ramesh et al.,1989; Bhattacharyya et al.,1992), dry deciduous forest in Korzi, Andhra Pradesh (Yadav and Bhattacharyya, 1996), Western Ghats of Kerala (Bhattacharyya et al., 2007; Borgaonkar et al., 2010), upper Narmada river basin in Central India (Wood, 1996) and dry deciduous forests of Madhya Pradesh (Shah et al., 2007; Somaru et al., 2008). These exploratory studies points to the usefulness of tree ring data for dendroclimatic analysis, especially in regions of seasonal precipitation.

2.5 Wood Variation

It is a well known fact that wood is one of the end product of forestry operations. The large number of studies on the topics like wood properties, and the causes of wood variation itself reflect its very importance. According to Downes and Raymond (1997), even though voluminous literature are available on the concerned topic, only a few has got recognition so far due to the confusing and contradictory nature of the literature which makes it difficult for a beginner to make use of those available information.

2.5.1 Sources of wood variation

Wood is a variable substance with difference occurring among species and genera, among geographical sources within a species and among trees within geographic source as well as within each individual tree (Zobel and Van Buijtenen, 1989). Among the different types of variations, tree to tree variability is large, compared to the difference within a species. Those property variations that arise from apical or cambial aging and positional effects of the crown are considered as intrinsic variations and those variations occurring due to the factors like environment, site conditions and silvicultural treatments are regarded as extrinsic (Perera et al., 2012). Therefore for the efficient use and productivity of wood, thorough understanding of the wood property variation patterns among trees, and among trees between and within species is needed.

Variation can be found among the segments of a species that grow in different environment within a species range (Callaham, 1964; Burley and Wood, 1976). All the wood properties are determined by its genetic factors and environmental factors and also by an interaction of the genetic potential of the tree with its living environment. This variability of wood accounts for its greater utility. But on the other hand, a major industrial need is to have greater uniformity Zobel (1984). Larson (1969) states that the greatest wood quality problem facing all wood using industries is lack of uniformity or in other words these wood variations results in variation in quality and thus in production inefficiency.

The area of wood variation and its control needs great attention and more research works are to be conducted on the same. According to Zobel and Buijtenen (1989) all these information should be known by tree grower, tree breeder and the tree harvester as well as by those who ultimately convert wood into a saleable product. Intensive studies of variation within a species which are necessary for tree improvement programmes have already been conducted in species such as on the loblolly pine (Thor, 1961), on jack pine (Yeatman, 1967), and on virginia pine (Lamb, 1973; Barnes et al., 1977).

2.5.1.1 Variation within and among trees

In general, most of the trees show variability in wood properties along the radii (i.e. from the pith to periphery), from the base to the top of the tree (vertical variation), within an annual ring, and sometimes even on different sides of the tree in relation to the sun and temperature (Sluder, 1972). The wood properties variation in trees is highly linked with their respective rotation system, for example Bendtsen (1978) states that the quality differences between wood properties of trees from natural and manmade forests are associated with the short rotation and resulting high proportion of juvenile wood. The variation within tree is generally hard to tackle since it is formed as the result of a fixed developmental pattern. At the same time, by controlling tree growth, the within-ring differences can be modified to some extent. Zobel and Buijtenen (1989) point out that through tree breeding and silvicultural manipulations, including fertilization it is possible to produce uniform wood with little variation.

2.5.1.1.1 Tree to tree variability

The tree to tree differences in wood properties within a species or within a provenance are large. Harris (1961) suggested that the difference in specific gravity among trees of same age grown at any one site can amount to 60 percent. For *Eucalyptus camaldulensis*, Chudnoff (1961) reported that, the variability among trees on the same site is more significant than the average differences between sites. Above studies reveal that, both in softwoods and hardwoods the variation within trees or within a provenance is often greater than that between species.

The tree to tree variation within a species is relatively constant for a particular provenance. For example, range of specific gravity in mature loblolly pine is always about 0.20, if 50 trees of same age are randomly sampled on the same site. At the same time there are studies which state that tree to tree variation is so large that it can even mask other causes of wood variability (McKimmy, 1959). Therefore, there is a pertinent need to conduct studies on wood properties for better strength and quality prediction.

2.5.1.1.2 Variation within trees

The variation within trees includes within-ring difference, variability from centre (pith) of tree to the outside (bark) and differences associated with different heights in the tree. The variability within a single tree is found to be higher, than the variability among the trees growing on the same site or between trees growing in different sites (Larson, 1967).

2.5.1.1.3 Variability within annual ring

Early wood/latewood difference itself is generally considered as the example for wood variation within an annual ring. In Douglas- fir, Andrews

(1986) reported high level of variability in the properties like specific gravity and chemical composition between early wood and latewood within an annual ring than between sapwood and heartwood of the same tree. Besides, early wood and late wood difference, transition wood forms an intermediate stage between early wood and late wood and is responsible for much of the variation in wood properties in juvenile wood.

Distribution of cell types within the ring has a great effect up on wood properties. Compared to softwoods, hardwoods have great differences in cell type and structure within an annual ring. Ring porous hardwoods like teak have a section of large sized vessels formed in the early part of the growing season, whereas diffuse porous hardwoods have quite uniform vessels throughout the ring which shows less within-ring variability. Within ring variation is determined by the growth pattern within the plant and Isebrands and Hunt (1975) suggested fertilization as a useful method for modifying the within ring variability.

2.5.1.1.4 Variation from pith to periphery

The radial pattern of variation is generally influenced by the proportion of juvenile and mature wood content. The radial change in wood properties varies in magnitude and type in different species. According to Zobel and Buijtenen (1989) the variation is found to become more abrupt in severe and short lived, initially fast growing species than in longer lived ones.

2.5.1.2 Wood variation related to provenance in plantation grown trees

Wood characteristics will vary greatly within the range of a species as well as localities in which they are grown. The variation within the species is found due to the differences in latitude, altitude, soil etc. The average differences in plantation wood grown from different geographic seed sources are not strongly genetically determined but usually are a response to the differing environment into which the trees have been moved (Talbert and Jett, 1981). For example, loblolly pine (*Pinus taeda*) has a high specific gravity in the southern part of its range and a relatively low specific gravity in the northern range. In exotics high level of variations are encountered since they are grown under more extreme environment (Biblis, 1969).

2.6 WOOD PROPERTIES

2.6.1 PHYSICAL PROPERTIES

2.6.1.1 Specific gravity

Specific gravity is defined as the amount of wood substance or biomass deposited per unit volume of living tree trunk, and thus is a factor influencing the amount of forest biomass (Wiemann and Williamson, 1988; Woodcock, 2000). Wood density is one of the important factors that determine the economic utility of wood for paper and pulp making as well as for solid wood purposes. The basic density is also used to estimate carbon stored in the woody stems of trees and has an appreciable influence on many solid wood properties and conversion processes, including cutting, gluing, finishing, rate of drying and paper making (Ilic et al., 2000).

The wood density is considered as one of the most significant property which determines the end use of the wood (van Buijtenen 1982; Bamber and Burley, 1983). De Guth (1980) correlated wood density with strength properties of wood, pulp yield and pulp quality. For most of the end uses like pulp and paper production or for solid wood products uniform wood density is the mostly preferred quality. In hardwood species, stiffness and strength are determined mainly by wood density (Huang et al., 2003; Innes, 2007), as well as by cellulose microfibril angle, the proportion of lignin, extractives, and interlocked grain; and the extent of spiral grain (Chafe, 1990; Aggarwal et al., 2002; Huang et al., 2003).

Specific gravity is one of the most extensively studied property mainly due to its relative easiness of measurement and generally high heritability. Zobel and Jett (1995) reported that density in eucalypts has been under strong genetic control, with individual heritabilities ranging between 0.4 and 0.84 (Otebeye and

Kellison, 1980; Wang et al., 1984; Malan, 1988; Borralho et al., 1992; Zobel and Jett, 1995). Genetic correlations between basic density and growth rate have been weak but often unfavourable (Malan, 1988; Borralho et al., 1992).

There are studies which highlight the relation between humidity and density. The specific gravity of wood showed considerable difference between species within provenance and between provenances. Trees from the drier region showed a higher average density (average 0.78) than that of trees from the more humid region (Morales, 1987). Barnes et al. (1977) elucidated the relationship between wood density and humidity in *Pinus caribea*, reported an 88 percent correlation between wood density and soil moisture deficit. Plumptre (1984) found that *P. caribaea* grown in climates with a pronounced drought had a higher density.

Teak seed brought from Burma and grown in Trinidad were found to produce trees with lower specific gravity than the teak trees of other seed origin (Scott and MacGregor, 1952). The influence of growth rate is expected to be more than the seed source difference for the specific gravity variation. Studies in *Acacia mangium* and *Acacia auriculiformis*, show that mechanical properties and specific gravity were much dependent upon species, provinces and site (Sahri et al., 1998a).

2.6.1.1.1 Radial variation in wood specific gravity

Variation of specific gravity in the radial direction has been studied for many species. The studies showed that from pith to periphery the specific gravity was found to be following an increasing trend, for example in species like *Swietenia macrophylla, Liquidambar styraciflua, Liriodendron tulipifera* and others have showed an increase in specific gravity from pith outward (Briscoe et al., 1963; van Eck and Woessner, 1964; Webb, 1964; Herpka, 1965; Hunter and Goggans, 1968; Sluder, 1970). Hans et al. (1972) reported an increase of specific gravity of *Eucalyptus grandis* from 0.414 in the central segment to 0.472 in the outer segment along radial direction. In species like *Grevellia robusta, Acacia auriculiformis and Acacia mangium*, Shanavas and Kumar (2006) got the similar result of increasing specific gravity from pith to bark. Espinoza (2004) analysed the wood specific gravity variation in *Gmelina arborea* plantations in western Venezuela and the result showed that specific gravity increases from pith to bark.

According to Wiemann and Williamson (1989), the increase in specific gravity with distance from the pith is a common trait among tropical wet forest species and this increase appear to be associated with the growth strategies of trees and their environments. Most studies indicate that high wood density in ring porous hardwoods is associated with fast growth (Guiher, 1965; Panshin and de Zeeuw, 1980; Baas, 1982; Zobel and van Buijtenen, 1989; Tsoumis, 1991; Guyette and Stambaugh, 2003; Saranpaa, 2003). Specific gravity was found to be low in wet, tropical environments and higher where conditions were drier and /or colder (Chudnoff, 1976; Morales, 1987; Wiemann and Williamson, 1989), but no significant difference in basic density between wet and dry locality teak were reported by Bhat et al., (2004). A study conducted in Costa Rica by Wiemann and Williamson (1989) revealed that, in dry forest species, specific gravity increases by 20 to 80 percent from pith to bark, 20 to 40 percent in montane forest species, and 20 to 70 percent in some tropical wet forest species. Woodcock et al. (2000) reported a specific gravity increase of 10 to 40 percent in the swamp and flood plain vegetation of the Tambopata region of Peruvian Amazonia, specific gravity was significantly lower at two riverine sites than in upland forest or swamp-forest. Wiemann and Williamson (1989) reported that even within a species, specific gravity may vary between wet and dry forest sites, for example *Ceiba pentandra* which had higher specific gravity in dry forest.

2.6.1.1.2 Specific gravity variation from base to top

Many trees have wood properties that vary at different heights along the stem. In conifers, as in hardwoods, the effect of height on wood properties is strong (Zobel and Buijtenen, 1989). Espinoza (2004) studied mean specific gravity variation from the base to the top of the tree in *Gmelina arborea* and found that mean specific gravity varied for height categories. They were 0.442, 0.432, 0.419, 0.430, and 0.440 for stump, DBH, half, 3/4, and top, respectively, with the specific gravity of stump and top being significantly larger than the specific gravity at half height. It was also evident that specific gravity decreased from stump to half of the total height, then increased towards the top of the stem. Moreover, no correlation was found between specific gravity and height of the tree.

Moya and Munaz (2010) observed a significant decrease in specific gravity with increasing tree height in *Acacia mangium, Bombapcosis quinata, Swietenia macrophylla* , *Terminalia amazonia* and *Terminalia oblonga*. However, no significant relationship was found for specific gravity with height in *Cupressus lusitanica, Alnus acuminata* and *Vochysia guatemalensis*.

2.6.2 Shrinkage

Wood shrinkage is one of the best examples for the anisotropic property of wood. Shrinkage process is constituted by a very complicated swelling or shrinkage behaviour with the adsorption or desorption of bound water below fibre saturation point. The swelling or shrinkage of wood ratio is generally 10 (tangential): 5 (radial): 0.1 to 1 (longitudinal). The shrinkage results in various dimensional changes like cracks in lumber, internal stresses, many other defects etc. and are undesirable characteristics from the timber utilization point of view. On the other hand, swelling and shrinkage could also be considered as intelligent characteristics of wood in response to the atmosphere (Okuma, 1998). Therefore it is important to have a better understanding of the swelling and shrinkage behavior in wood.

Miranda et al. (2011) studied the wood properties of teak in East Timor had reported that, the average wood shrinkage from green to the oven-dry state was 3.5 percent and 5.2 percent for the radial and tangential directions respectively and 7.6 percent for volumetric shrinkage. The ratio of tangential to radial shrinkage was found to be only 1.48 which indicates a low risk of deformation in wood during drying as per the findings of Rijsdijk and Laming (1994). A similar value for teak shrinkage were reported by Baillere and Durand (2000), where they recorded a range of 5.7 percent to 8.4 percent for the volumetric shrinkage of teak wood from natural forest trees, and in another study Moya and Ledezman (2003) also reported a volumetric shrinkage of 6.5 percent to 7.5 percent for 10-year old teak trees from plantations, quite similar to the values reported by Miranda et al. (2011).

Shukla et al. (1999) carried out studies on shrinkage properties in plantation grown Andaman padauk (*Pterocarpus dalbergioides*) and compared those values with the natural grown andaman padauk and that of teak. The results on average radial(R), tangential(T), longitudinal(L) and volumetric shrinkage from green to oven dry condition indicated that Andaman padauk had all those values comparable to that of teak. Shukla et al. (1994) in another study compared the shrinkage properties of *Cinnamomum cicedodaphne* and *Dysoxylum hamiltoni* with that of teak, and showed a high value for their tangential, radial and volumetric shrinkages with respect to teak. The shrinkage properties studies were conducted in *Grevillea robusta* and *Terminalia myriocarpa* by Khanduri et al. (2000) and reported a higher value of shrinkage than teak in both species. In the same study, they compared shrinkage values of the above species from different localities. It was found that shrinkage values of *Grevillea robusta* from Karnataka locality were higher compared to that from Dehradun.

Shanavas and Kumar (2006) studied shrinkage properties in species such as *Acacia mangium, Acacia auriculiformis* and *Grevillia robusta*, and found that mean radial, tangential and volumetric shrinkages for *Acacia auriculiformis* were significantly lower than that of *Acacia mangium* and *Grevillia robusta*. It was also noticed that while shrinkage values were not substantially different among radial positions, *G. robusta* exhibited highest radial and tangential shrinkage for the outer position. *Acacia mangium* showed a reverse trend for tangential shrinkage. Moreover, volumetric shrinkage also decreased from inner to outer position in *A. mangium* but increased from inner to outer positions in *G. robusta*.

In the study on shrinkage properties of coppiced *Eucalyptus tereticornis* and non-coppiced *Eucalyptus tereticornis*, it was found that, the shrinkage values were comparable in both the cases and are much higher compared to teak. It was also noticed that, longitudinal shrinkage was more in coppiced wood (Sharma et al., 2005). Studies made earlier in *Eucalyptus tereticornis* also indicated that shrinkage values were very high (Jain, 1969; Kothiyal et al., 1998). The higher values of shrinkage were the main causes of dimensional instability of the timber from both non-coppiced and coppiced wood. Rao and Hemavathi (1992) indicated the occurrence of tension wood in this species as one of the reasons for such high shrinkage.

Donaldson et al. (2004) studied shrinkage properties of compression wood in radiata pine and noticed abnormally high longitudinal shrinkage in the species especially in juvenile wood. It was also observed that the relationship between longitudinal shrinkage and microfibril angle was different in compression wood compared to normal or opposite wood, with shrinkage in compression wood being much more sensitive to changes in microfibril angle. Juvenile wood has a high fibril angle that causes excessive longitudinal shrinkage, which may be more than 10 times that of mature wood (Yang et al., 1992). Compression wood and spiral grains are also more prevalent in juvenile wood than in mature wood and contribute to excessive longitudinal shrinkage. Furthermore, longitudinal shrinkage is greater in early juvenile wood than in late juvenile wood.

2.6.3 Bark thickness

Bark plays a critical role in the life of a tree when it is standing (Marshalll et al., 2006). In North America, Heath et al. (2009) found that the amount of tree bark varied by species and can range from12 to 20 percent of the total wood volume. The importance of tree bark lies in several aspects: (1) it provides protection for tree growth; (2) it can serve as a source of energy or as other specialty products like mulch or medicine; and (3) it influences merchandising decisions as most logs are sold based on their inside bark volume. Therefore, knowledge of bark thickness and the ability to predict it accurately are important as the use of an inaccurate estimate can result in a loss of value of up to 11 percent to a forest landowner (Marshall et al., 2006).

Since total bark volume of standing trees can be roughly derived if the information of the bark thickness at breast height is available, earlier studies on bark thickness mainly focused on predicting its thickness at breast height (Monserud, 1979). As the bark thickness varies vertically in a tree many works has been done by taking in to account the bark taper along tree stems (Maguire and Hann, 1990; Laasasenaho et al., 2005; Brooks et al., 2009). Models for both absolute and relative bark thickness (stem bark thickness divided by bark thickness at breast height) have been developed and demonstrated in several studies (Maguire and Hann, 1990; Johnson and Wood, 1987; Laasasenaho et al., 2005; Laar 2007).

Many models were developed for measuring the standing volume of a tree. Most of them used independent variables such as inside bark diameter at breast height for a more or less accurate prediction (Gordon, 1983; Cao and Pepper, 1986; Johnson and Wood, 1987).

The factors influencing bark thickness of a tree include the species category, rate of growth, the genetic constitution of each tree, and position along the bole (Laasasenaho et al., 2005). According to Husch et al., (2003) developing a local bark thickness equation can take a significant amount of work since one bark thickness function with the same set of parameter values cannot be unanimously applied to all trees, even for the same species.

2.6.4 Heartwood – Sapwood ratio

Heartwood formation in trees has attracted the focus of many scientists, and numerous investigations have been carried out to throw light on this phenomenon. Many of these are summarised by Bamber and Fukazawa (1985), Hillis (1987), and Taylor et al. (2002). Usually, scientists have reported the heartwood in relative units, e.g. heartwood as a proportion of the diameter, proportion of the cross sectional area or of the volume of a tree. This is probably useful when studying the heartwood formation process from a biological point of view and also for the pulpwood industry

The effects of management practices on heartwood formation are not known. In normal forestry conditions, heartwood formation begins at the age of 4 years. The important questions are whether fast growth itself will result in quicker formation of heartwood and whether intensive management practices and site conditions influence yield of heartwood in short rotation plantations (Bhat, 2000).

Only a few studies have been conducted on the anatomical changes associated with heartwood formation in teak. Datta and Kumar (1987) studied the histochemical changes in the transition zone between sapwood heartwood regions. Nobuchi *et al.* (1996) investigated some characteristics of heartwood formation. The proportion of heartwood in teak trees is an important factor for wood quality. During the process of heartwood formation, certain chemical processes take place, which improve durability and change the colour of the wood (Higuchi, 1997). Thulasidas and Bhat (2009) compared sapwood-heartwood percentages in home garden teak and forest plantation teak. The general notion that home garden teak has a larger proportion of sapwood became baseless and no significant differences being found between the heartwood-sapwood ratio of home garden and forest plantation teak.

Many studies have been conducted so far on the strength property variation between heartwood and sapwood. Shukla et al. (1994) studied variation of strength properties from pith to periphery in Eucalyptus hybrid and found that strength increases from pith to periphery within the heartwood region but decreases in the sapwood region.

The quantity of sapwood that a tree contains is important to physiologists (Becker et al., 2000), ecosystem scientists (Berninger and Nikinmaa, 1997) and wood technicians (Semple and Evans, 2000). The ability to better predict sapwood and heartwood quantity in a stand will help silviculturists make better informed decisions regarding forest management and harvesting, help tree owners ensure fair prices for the logs, and help mills plan for the wood that they will be processing.

Searle and Owen (2005) assessed species, provenance and within tree variation in heartwood percentage for different Acacia species (40 provenances) and *Eucalyptus nitens* (one provenance) from southern Australia. He observed some association between percentage heartwood and basic density at the species level but no association was found between provenances.

The proportion of sapwood and heartwood in a tree varies genetically with genera, species and families, and with factors such as silviculture, growing conditions and tree age (Hillis, 1987; Wilkins, 1991). Heartwood content is also found to have a direct link with the tree size (diameter and height) (Gominho and Pereira, 2005; Miranda et al., 2006). It is generally accepted that heartwood width is more clearly a function of tree age (Hillis and Ditchbume, 1974). A clear relationship between sapwood width and tree age in species such as Tamarack (*Larix laricina*) and Jack pine (*Pinus banksiana*) was reported by Yang et al. (1985). At the same time previous studies reported contradictory results in some pine species (Todorovsky, 1966).

The estimation of heart wood content helps to define differences in durability and other wood characteristics (Wiemann and Williamson,1989). The heartwood percentages of some of the plantation grown tree species such as *Acacia mangium, Alnus acuminata, Bombacopsis quinata, Cupressus* *lusitanica, Swietenia macrophylla, Terminalia amazonia, Terminalia oblonga* and *Vochysia guatemalensis* in Costa Rica were determined by Moya and Munoz (2010) . The result showed a low amount of heartwood content in species like *B. quinata, V. guatemalensis* and *T. Amazonia* and almost nil in *A. Acuminate.* Low heartwood content was documented in tropical plantation species, such as *T. grandis* (Perez and Kanninen, 2003; Moya and Perez, 2008), *G. arborea* (Moya, 2004), *A. mangium* (Lee et al., 1999) and *V. guatemalensis* (Moya et al., 2009).

Miranda et al. (2009) studied variation of heartwood and sapwood in 18 year old *Eucalyptus globulus* trees grown with different spacing and suggested that, the tree possess a considerable proportion of heartwood at breast height which was very highly and positively correlated with stem diameter.

There are many studies which point out tree diameter as a major factor for influencing the heartwood formation than tree age; (*Eucalyptus grandis* (Wilkins, 1991), *Tectona grandis* (Bhat, 1995), *Pinus contorta* (Yang and Murchison, 1992), *Juglans nigra* (Woeste, 2002), *Acacia melanoxylon* (Knapic and Pereira, 2005) and *Pinus canariensis* (Climent et al., 2002)).

Gominho and Pereira (2005) examined the effect of spacing on heartwood development in 9 year old *E. globulus* trees and found that spacing influenced heartwood content because of its impact on tree dimensions, especially diameter. A study on variation in heartwood diameter along the stem in scots pine in Norway observed a decrease in heartwood diameter from base to top (Flaete and Vadla, 2008).

2.6.5 Moisture Content

The estimation of wood moisture content has got considerable importance in wood quality studies since it has many direct and indirect influences on various quality related parameters. Specific gravity and moisture content are usually negatively related within a species; higher the specific gravity, lower the moisture content (Zobel et al., 1968). For example, trees of the genus Leucaena (Brewbaker and Hutton, 1979) are considered to be ideal for energy production because of their dense wood with low moisture content. Williams and Hale (2003) reported that wood moisture contents have significant influence on fungal decay action in Corsican pine. Moisture content found to differ significantly with respect to species. Sekhar (1988) observed mean moisture content of 76.6 percent for teak from Malabar, Nilambur and Coimbatore, while Sahu (2005) reported higher percentage of moisture content in hardwood species like *Albizia odoratissima* (84.6 %) and *Samanea saman* (135.6 %). Same study reported a lower moisture content for *Dalbergia latifolia* (74.5 %) compared to teak. In *Swietenia macrophylla*, Sindumathi (2012) observed an increase in moisture content towards periphery region, but it did not show any definite radial pattern of variation in *Pterocarpus dalbergioides* and *Pericopsis mooniana*.

2.7 ANATOMICAL PROPERTIES

The wood formation process is a result of action of environmental and genetic factors which act in varying degrees and therefore same factors are responsible for the variation in anatomical properties in wood. Most of the anatomical parameters vary significantly from the pith outwards in a tree. According to Bhat et al. (2001) wood anatomical properties show variation in the region of juvenile and mature wood. Studies have illustrated the effect of crown proximity during the wood formation on variation of anatomical properties of wood within the main stem of a tree (Larson, 1964; Isebrands, 1972). Panshin and De Zeeuw (1980) reported that any significant differences in mechanical performance between sapwood and heartwood are usually attributed to the radial changes in wood density or anatomical structure.

2.7.1 Vessel morphology

The vessel dimensions/morphology is one of the major parameters studied in wood anatomical investigations. Vessel morphology is very much dependent on environmental factors; Varghese et al. (2000) studied the variation in growth and wood traits among nine populations of teak in peninsular India and found a significant variation in the size of vessel elements of the samples collected from

Kalakkad (Tamil Nadu) and Allapally (Andra Pradesh). The same study indicated that latitudinal effects have little influence on vessel element length and vessel diameter.

A study by Ishiguri et al. (2009) on the radial variation of anatomical characteristics of *Paraserianthes falcataria* planted in Indonesia reported that the vessel diameter of the species showed a rapid increase up to 5 cm from the pith and then showed an almost constant value. Teak from relatively fast growing provenances showed wide rings with a gradual transition between early and latewood while vessels become smaller towards the latewood region with more gradual changes in vessel size (Bhat and Priya, 2004). Sharma et al. (2005) reported that vessel diameter showed an increasing trend in *Eucalyptus tereticornis* while vessel element length did not show any definite trend from the pith outwards in both non-coppiced and coppiced wood. Carlquist (1966) and Zhang et al. (1988) found that vessel diameter and vessel element length decrease with increasing aridity and also with increase in vessel frequency. Schmitz et al. (2006) studied vessel characters in relation to salinity in mangroves and concluded that environmental responsiveness of vessel diameter to soil water salinity was remarkably low in either rainy or dry season.

The other parameters like vessel area and vessel distribution determines the suitability of hardwoods for pulping. Vessels were reported to be absent at the beginning of growth rings of some Eucalyptus species viz. *Eucalyptus nitens* (Sandercock et al.,1995), *E. regnans* (Bisset and Dadswell, 1950) and *E. delegatensis* (Amos et al., 1950). Vessel numbers were reported to be lower in the latewood of *E.* nitens, *E. globulus* and *E. regnans* (Williams, 1994).

Vessel lumen diameter (VLD) is another property which is having significant importance in wood anatomical studies. Vessel lumen diameter generally shows radial variation from centre to bark region. Studies by Furukawa and Hashizume (1987), Ohbayashi and Shiokura (1990), Raczkowska, (1994), Peszlen (1994), Lei et al. (1996) Gartner et al. (1997), Raczkowska and Fabisiak

(1999), Bhat et al. (2001) reported similar variation trend for vessel lumen diameter, i.e. the vessel lumen diameter increases from pith outwards. Tsuchiya and Furukawa, (2008, 2009) studied the relationship between radial variation in vessel lumen diameter and the stages of the radial growth in four species namely *Castanea crenata, Quercus serrata, Populus simonii* and *P. beijingensis* and reported that vessel lumen diameter increased during the early and the middle stage, and become stable in the later stage.

A study on relationship between water availability and selected vessel characteristics in *Eucalyptus grandis* and two hybrids were conducted by February et al. (1995) in which it was found that in *E. grandis* and in the hybrid *E. grandis* x *E. camaldulensis*, vessel diameter and vessel element length increased from the dry to the wet treatment as water uptake through transpiration increased and no significant correlation was found between available water and vessel frequency. On the other hand, for *E. grandis* x *E. nitens*, only vessel frequency was significantly correlated with water uptake. Thus the results highlight water use efficiency of *E. grandis* x *E. nitens* over *E. grandis*. For many genera and species, diameter and vessel element length decrease while vessel frequency increases with decreasing water availability (Carlquist, 1975; Baas and Schweingruber, 1987; Walt et al., 1988; Wilkins and Papassotiriou, 1989; February,1993).

2.7.2 Ray morphology

The size and distribution of rays and vessels in hardwoods affect wood quality and utilization, both for solid wood and paper and pulp. Wood figure in maple is related to the size and distribution of rays. The ray cells are short and usually thin walled and so contribute little to the strength properties of paper. In solid wood, the ray tissue contributes to acoustic wave propagation in radial direction (Bucur, 1995). Ray width is considered a useful character for wood identification of species groups of the maple group (*Acer spp.*) (Dakak et al., 1999). For beech, Keller and Thiercelin (1975) did not observe significant correlations between specific gravity and the proportion of rays or the number of rays per unit surface.

3.4 Interrelationship between wood physical and anatomical properties

Wood characteristics, including physical and anatomical properties are related to each other. Anatomical properties like structure and proportion of different wood tissues in wood, including dimensions of vessels, fibres, rays and parenchyma determine the physical properties, which in turn affect wood mechanical properties. Panshin and de Zeeuw (1980) pointed out that, in general terms, the density of wood depends on (1) the size of cells, (2) the thickness of the cell walls, and (3) the interrelationship between the two.

In hardwoods, it has been reported that high density is generally associated with an increase in fibre volume and a decrease in vessel volume (Taylor and Wooten, 1973). Ishiguru et al. (2009) studied radial variation of anatomical characteristics in *Paraserianthes falcataria* planted in Indonesia and found significant positive correlation existing between vessel percentage and basic density. They found no significant correlation between ray parenchyma percentage and basic density, but significant correlation was observed between axial parenchyma percentage and basic density. According to Taylor (1973), density always increased when there was an increase in fibre volume and decreased when the volume of parenchyma increased.

Fuentes and Hernandez (2008) studied effect of anatomy on the mechanical properties of Mahogany (*Swietenia macrophylla*) and concluded that mainly anatomical features, such as rays and vessels, rather than extractives, affect the mechanical behaviour of mahogany. These findings are in agreement with earlier results showing a negative effect of large and multiseriate rays on the mechanical properties of wood when loaded perpendicularly to their long axis.

Sharma et al. (2005) analysed specific gravity in coppiced and non-coppiced *Eucalyptus tereticornis*. The anatomical characteristics showed that in non coppiced wood the specific gravity was negatively related to vessel diameter.

2.8 Biochemical properties

2.8.1 Extractive content and heartwood colour

Teak wood is well known for its natural resistance against termites and borers (Becker, 1961; Thulasidas and Bhat, 2007; Lukmandaru and Takahashi, 2009). This merit is chiefly attributed by the amount of extractive content in the heartwood of teak. Lukmandaru and Takahashi (2009) have reported numerous bioactive compounds from teak wood. Also, a variety of compounds with varied degree of structure, belonging to different classes such as flavonoids, quinones, steroidal compounds, glycosides and phenolic acids have been identified and isolated from almost every part of the tree (Ohmura et. al., 2000).

For the evaluation of extractive content in teak wood, various organic solvents like acetone, n-hexane, ethyl ether, ethyl acetate, and ethanol have been used in many studies (Syafii et. al., 1987; Syafii and Yoshimoto, 1993; Ohmura et al., 2000; Syafii, 2002). Lukmandaru and Ogiyama (2005) have reported that extracts of ethyl alcohol and ethyl acetate of teak wood have strong bioactivity against termites.

Concern about environmental impacts of chemical wood preservatives has resulted in increased interest of natural wood durability. The natural durability of sapwood of most species is generally low, while heartwood can be more resistant to bio-deterioration. Heartwood, the innermost and older wood within a tree, is often characterised by deposits of resinous, phenolic and other compounds which contribute considerably to the colour of the wood. These deposits are also mainly responsible for the enhanced durability of heartwood (Bootle, 1983; Boland et al., 1984). Species with attractive heartwood colour and grain generally attract the highest returns, as they are used for the highest value products including structural and decorative timbers for building, joinery and furniture (Bird, 2000). Some

Australian acacias, such as *A. melanoxylon* (blackwood), are valued for their attractive heartwood but little research has been conducted to understand the genetic variation of this characteristic as the basis for tree improvement (Searle, 2000). Kuo and Arganbright (1980) and Grabner (2002) presented evidence for a direct influence of extractives on the modulus of rupture and the modulus of elasticity, in addition to their effect on wood density.

MATERIALS AND METHODS

MATERIALS AND METHODS

3.1. MATERIAL

Teak wood samples were collected from the saw mills and major ports of import of timber in South India. Map showing the location of samples acquired is given in (Figure 1). A preliminary sawmill based survey was carried out to identify the timber markets which deals with different varieties of teak. On the basis of the details obtained, the samples (teak discs; plate 1) were collected from sawmills and the timber dealers of major timber ports of South India viz. Mangalore port, Tuticorin Port, etc. Teak samples from 14 locations were collected which include samples from Nilambur (Kerala), Ranni (Kerala), Konni (Kerala), Malayatoor (Kerala), Vadavar (Tamil Nadu), Betul (Madhya Pradesh) and the samples from outside India viz. Thailand, Myanmar (Asia), Trinidad and Tobago (N. America), Ghana, Camaroon, Sudan, Tanzania, Benin (Africa).

3.2. METHODOLOGY

Wood property analysis was carried out in department of Wood Science, College of forestry, Kerala Agricultural University during 2011-2013. The samples from each location are categorised in two groups on the basis of their growth rate by assessing the average ring width i.e. fast and slow. The variation in wood anatomical, physical and biochemical properties among the fast and slow categories were observed and analysed using standard methodologies.

3.2.1 Width of growth ring

In the study, the width of growth ring was determined from the teak sample disc. The width of every growth ring in four perpendicular radii was measured, whereby two radii were from the smallest diameter of the disc (Plate 2a and Plate 2b). For each disc, the growth rings were individually followed around the discs (especially in discs with irregular boundaries), also the false rings were

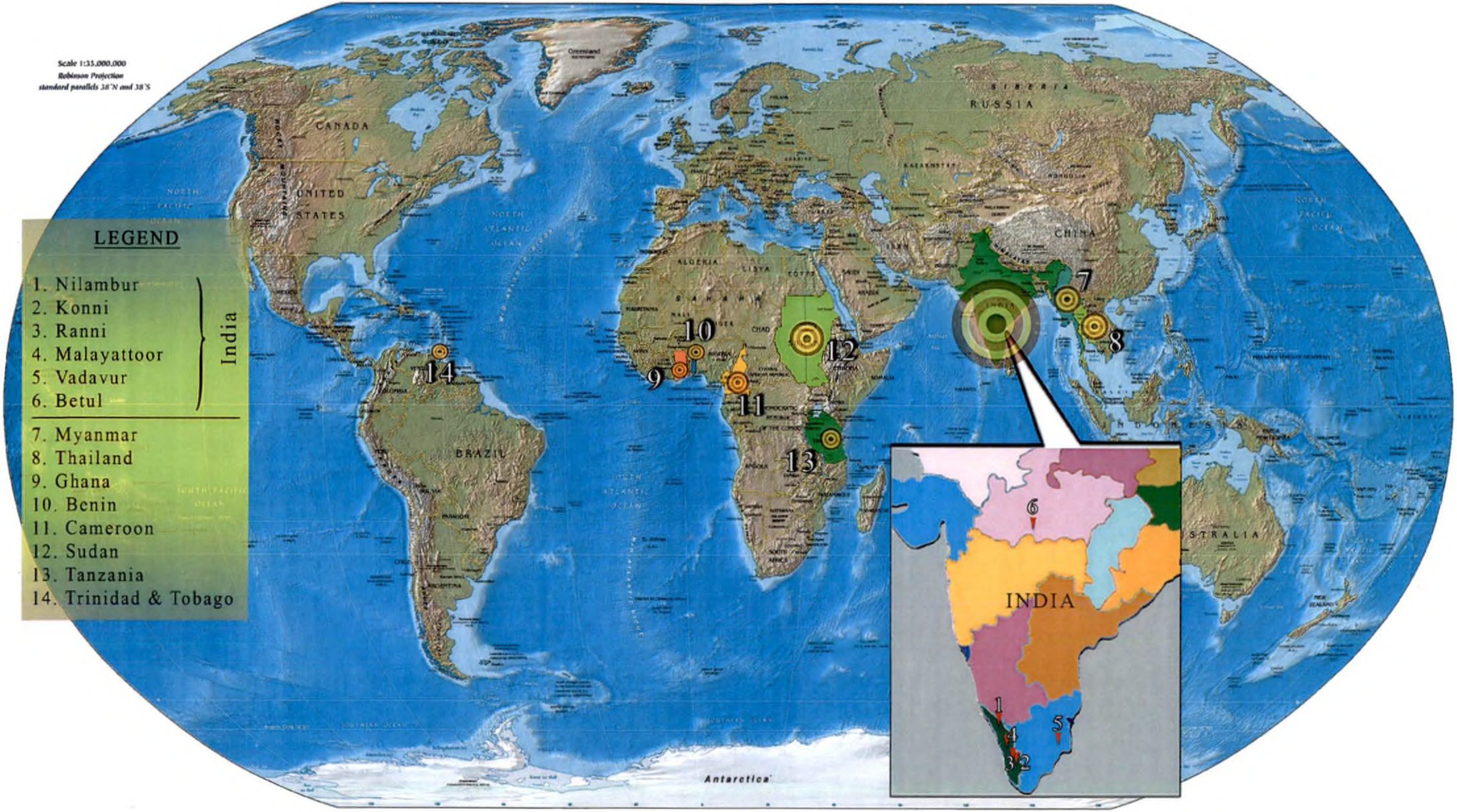


Fig 1. World map showing country of origin of teak samples studied.

Plate1. Cutting of sample discs using band saw

Plate 2a. Tree disc for average ring width measurement

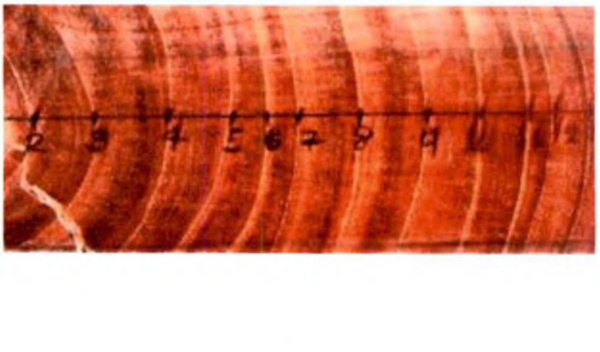


Plate 2b. Ring width measurement

distinguished macroscopically from true annual ring cross-checked further by microscopic observations.

3.3 PHYSICAL PROPERTIES

3.3.1 Specific gravity

Samples of size 2 cm x 2 cm cross section and 6 cm in length were converted from each disc as per IS2455: 1990 (ISI, 1990; plate 3). The specific gravity of wood is expressed as the ratio of the weight of the wood to the weight of an equal volume of water. Specific gravity was measured using a specific gravity module attached to an electronic balance (Schimadzu AUY220; plate 4). The converted core samples from each tree representing pith, middle and periphery were used for specific gravity measurements. Specific gravity was estimated on fresh, air dry and oven dry weight basis.

To obtain specific gravity on fresh weight basis, the specimens were soaked in water for 48 hours to regain moisture and specific gravity was assessed using the balance. Similar observations were repeated in the wood samples when they attained moisture percentage level of 12 to 15% to obtain air dry specific gravity. Oven dry specific gravity was measured after drying the wood samples in an oven, set an approximately constant temperature of $102^0C\pm1^0C$, for such a time as is needed to make its weight constant.

3.3.2. Heartwood percentage

In order to assess heartwood - sapwood percentage, graphical method was followed. Percentage of heart wood and sap wood was determined based on the colour differentiation of inner and outer zone of the cross- sectional discs. Both heart wood and sapwood portions were traced using through a tracing sheet and area was calculated by using a graph paper. Heartwood sapwood area thus obtained was cross checked using the digimizer software (Version 4.1.1.0.).

Plate 3. Wood samples used for specific gravity estimation

Plate 4. Specific gravity module attached to electronic balance (Schimadzu AUY 220)

3.3.3. Radial and tangential shrinkage

Small blocks of size 2 cm x 2 cm and 5 cm long were collected from the wooden discs. These blocks were marked at the radial and tangential positions for assessing shrinkage. The samples were then measured at these positions for measuring radial and tangential lengths using a vernier calliper in the green condition (plate 5). Subsequent measurements were made at the same positions for assessing radial and tangential shrinkage at air dry (12% moisture content) and oven dry conditions (102 ± 1^0C) as per IS 1708 (part 4): 1986 (ISI, 1986). Radial (RS) and tangential shrinkage (TS) percentages were calculated using the following formula:

a) RS or TS from green to air-dry condition (%) = $\frac{\text{Lg} - \text{La x } 100}{\text{Lg}}$

b) RS or TS from air-dry to oven-dry condition (%) = $\frac{\text{La} - \text{Lo x } 100}{\text{Lo}}$

c) RS or TS from green to oven-dry condition (%) = $\frac{\text{Lg} - \text{Lo x } 100}{\text{Lo}}$

Where

Lg = Length of the specimen along radial or tangential plane at green condition (mm)

La = Length of the specimen along radial or tangential plane at air-dry condition (mm)

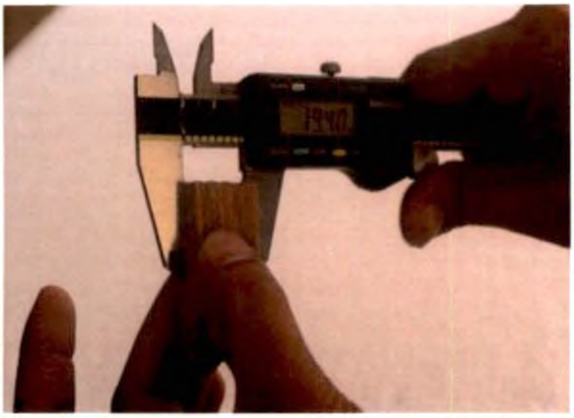
Lo = Length of the specimen along radial or tangential plane at oven-dry condition (mm)

3.3.4. Bark thickness

Bark thickness of the wood discs were measured at their major and minor axes using a vernier calliper and their averages were calculated.

3.3.5. Heartwood colour

Heartwood colour determination of the samples was conducted using Munsell system (1976). From the air dried (12 % moisture content) 5 cm thick



te 5. Measuring the dimensions of samples for
inkage

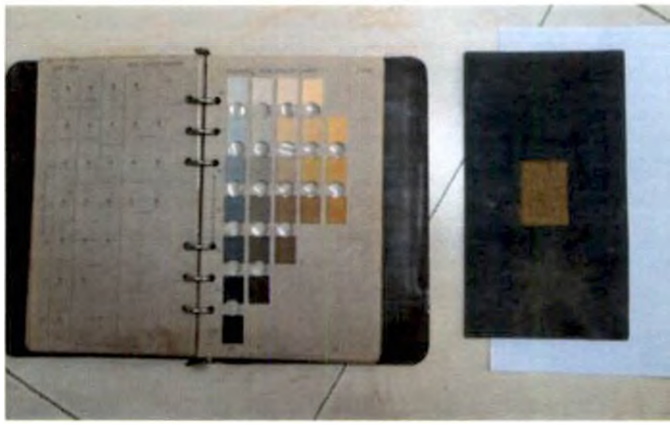
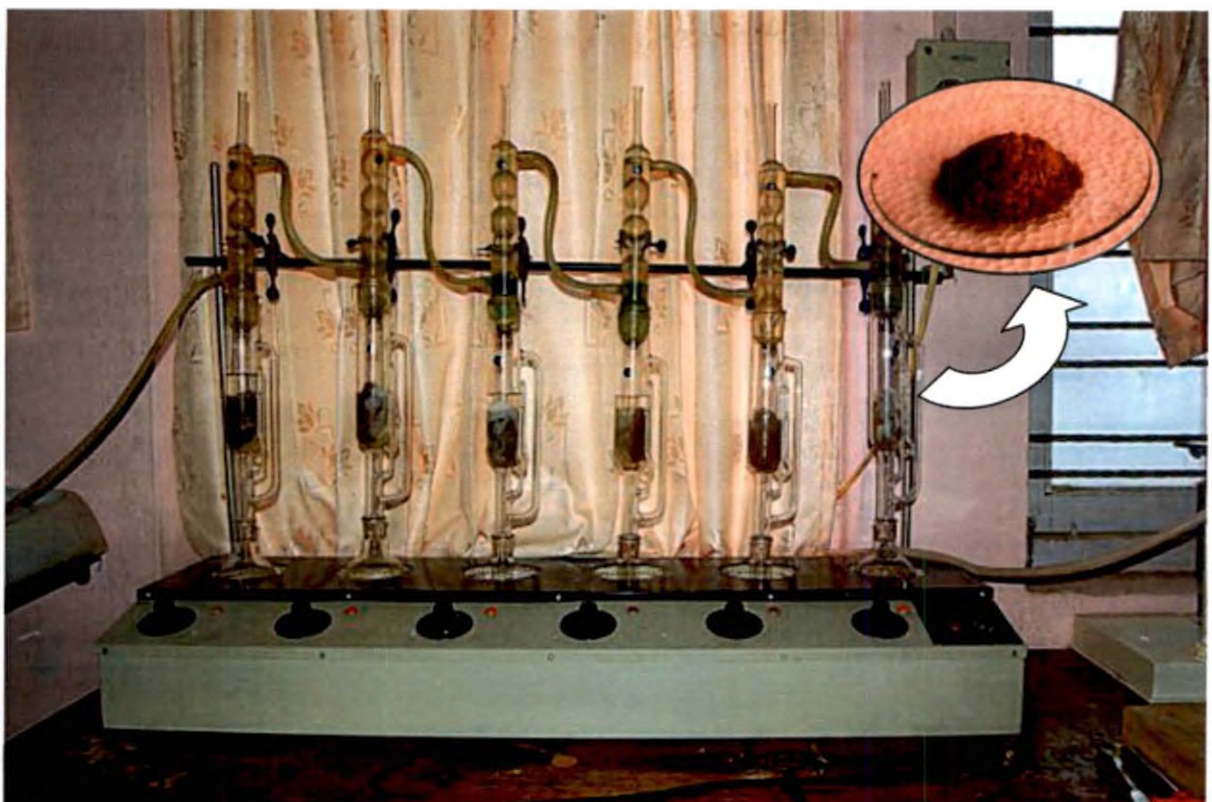


Plate 6. Determination of heartwood colour using
Munsell system



cross sectional disc, a radial strip of 3 cm width was cut from inner to outer heartwood in both radii excluding the pith. The two cut samples were ground in a mechanical grinder separately. The powder was passed through No. 40 (420 μm) sieve and retained in No. 60 (250 μm) sieve respectively. The colour of the samples was determined within a day after the sample preparation to avoid colour changes caused by oxidation or light.

Munsell notation of colour difference is considered for visual interpretation as influenced by personal judgement of colour. The powdered wood sample placed under the colour chart appears through the round openings, allowing easy comparison with the rectangular colour chips (plate 6). The colour is then identified by its hue, value and chroma. Hue value ranges from 9.9 R to 1.0 Y from red to yellow. The scale of value ranges from 0 for pure black to 10 for pure white. Value indicates the lightness/brightness of a colour. Chroma is the departure of a colour from its neutral colour of the same value. Colours of low chroma are sometimes called weak, while those of high chroma are said to be highly saturated, strong or vivid.

3.3.6. Moisture content

Moisture content (MC) was determined in accordance with ISO 3130 procedures. All test specimens were weighed to obtain the green weight (weight in green condition obtained by soaking the specimen in the water to regain the moisture) and then air dried till the weight became constant and the samples showed no further decrease in volume. The samples were then oven dried at a temperature of 102 ± 1 °C to constant weight to obtain the dry weight. The moisture percent of each test specimen was calculated as per the following formulas:

a) MC at green condition (%) = $\frac{\text{Green weight} - \text{Oven dry weight}}{\text{Oven dry}} \times 100$

b) MC at air dry condition (%) = $\frac{\text{Air dry weight} - \text{Oven dry weight}}{\text{Oven dry weight}} \times 100$

3.4 ANATOMICAL PROPERTIES

3.4.1. Microtomy

Small specimens of 1 cm^3 cube prepared out from the tree discs representing the pith, middle and periphery portions were used for carrying out sectioning for anatomical studies. Sectioning was carried using the sliding microtome (Leica SM 2000R) after softening the samples by heating in a water bath at 80^0C for few hours. Cross and tangential sections of 10-15μm thickness were prepared using the microtome (Plate 8).

3.4.1.2 Sectioning and staining

Thin sections were taken from the transverse and longitudinal surfaces of the wooden blocks and were stained using the procedure outlined by Johansen (1940). The sections were stained using safranin and washed through a series of alcohol solutions having different concentrations in the order of 70%, 90%, and 95% respectively. This washing was followed by dipping the sections in acetone and finally in xylene. The sections were taken out from the xylene and permanent slides were prepared using the DPX mountant.

3.4.1.3 Image analysis

Permanent slides were examined using an Image Analyser (Labomed-Digi 2; plate 9) which is provided with a microscope, digital camera, and a personal computer. Images of the sections were captured first and then measurements including length, diameter, thickness and proportion of fibres, vessels, and rays were made using the software labomed DigiPro-2.

3.4.1.4 Observations

Various parameters of vessels and rays including their area, diameter and number per unit area were noted from the image using the computer software (Labomed Digi Pro-2). Five observations were taken as replicates from the pith, middle and the periphery section and is expressed was micrometers (μm).

Plate 8. Sliding wood microtome (Leica SM 2000 R) used for wood sectioning

Plate 9. Image Anayser (Labomed Digi-2) used for anatomical quantification

From the tangential section of the wood samples, parameters such as ray height, ray width, and ray frequency were measured. Ray frequency was measured by counting the number of rays from a selected area in the section with the help of the image analysis software, Labomed-Digi Pro 2 and was expressed in number per micrometres (μm).

3.5 BIOCHEMICAL PROPERTIES

3.5.1. Extractive content analysis

The total extractive content of heartwood was determined for each of the sample to study its variation in each sample. The ASTM standard D1107-84 for the determination of alcohol-benzene solubility of wood was followed. Whole heartwood samples from pith to periphery in each radial direction was taken and powdered in a mechanical grinder. The powder was allowed to pass through No. 40 (420 μm) sieve and retained in No. 60 (250 μm) sieve. The test specimen consisted of 2g air-dried saw dust placed in the extraction thimble (30 mm x 100 ml) in the Soxhlet extraction apparatus (plate 7) (capacity 100 ml) and was extracted against 150 ml of ethyl alcohol and benzene (1:2 ratio) in the extraction flask continuously for 8 hours keeping the liquid boiling briskly. This facilitated 4 to 6 siphoning per hour. After evaporating the solvent from the extraction flask, the contents (extractive contents) of the flask were dried in an oven at 105^0 C for 1 hour, cooled in a desiccator and weighed to determine the percentage of extractive content based on moisture free saw dust.

3.6 STATISTICAL ANALYSIS

The samples from each location were divided in two groups on the basis of their growth rate as fast and slow. The observations were made at three levels viz., pith, middle and periphery within the tree discs, for studying the horizontal variation of wood properties within the trees for studying variation in anatomical, physical and biochemical properties and those three level observations were made as replications for studying the between tree variations. Thus grouping (fast and slow) and sub grouping (between provenances) makes a nested or hierarchical classification (Sokal and Rohlf, 2012), NESTED ANOVA was carried out to find variation that exist between fast and slow grown trees of varying localities using SAS (ver.10). The variation in physical properties such as, heartwood percentage, heartwood colour and bark thickness were found out by carrying out t-test and category wise (fast and slow) mean and standard deviation were tabulated. The inter-relationship between different wood properties was also studied through correlation analysis.

RESULTS

RESULTS

Results pertaining to variation in wood physical, anatomical and biochemical properties of teak samples studied as part of the investigation on the effect of rate of growth on different wood quality parameters of teak with reference to teak samples obtained from trees which were grown within the country as well as outside the country are presented under the following categories, (i) ring width, (ii) physical properties (specific gravity, shrinkage, moisture content, heartwood percentage, heartwood colour, bark thickness), (iii) anatomical properties (vessel morphology, ray morphology) and (iv) biochemical properties (extractive content).

4.1 Ring width

Teak samples collected from 14 different locations were subjected to ring width analysis. The results of ring width analysis were used to classify the samples into two categories viz. fast grown and slow grown. The samples having an average ring width ≥ 5 mm was categorized as fast grown, while those samples having an average ring width < 5 mm was categorised as slow grown (Table 1).

Table 1. Average ring width of teak samples from different locations

Sl. No	Location	Average ring width (mm)	Category (Rate of growth)
1	Nilambur	5	Fast
2	Vadavar	8	
3	Ranni	5	
4	Tanzania	5	
5	Benin	5	
6	Camaroon	5	
7	Ghana	6	
8	Konni	3	Slow
9	Malayatoor	3	
10	Betul	3	
11	Myanmar	3	
12	Thailand	4	
13	Sudan	4	
14	Trinidad	4	

4.2. Effect of sample age

For determining the effect of age of samples (based on number of rings) on the observed parameters, the physical, anatomical and biochemical properties were correlated with the sample ages. The result revealed an insignificant and wherever significant, a weak relationship between sample age and the observed wood properties (Table 2). Parameters such as specific gravity (oven dry), ray height and heartwood percentage showed significant differences (at 5 % level) and in the case of vessel diameter, vessel area, vessel frequency, ray frequency and extractive content differences were significant at one percent level. Specific gravity (oven dry) (-0.191), vessel frequency (-0.421) and ray frequency (-0.234) showed a weak negative correlation with sample age while ray height (0.161) vessel diameter (0.363), vessel area (0.362), extractive content (0.526) and heartwood percentage (0.569) showed a weak and moderate positive correlation. Since the effect of age on almost all the different wood properties studied was very less, the remaining comparisons done in the study were conducted regardless of the sample age. Therefore, in the present study, age of the samples can be considered to have little influence on wood properties and hence it was not included as a factor to be considered for subsequent comparisons and analysis.

Table 2. Correlation between wood properties and age of the sample

Wood Properties	**Correlation coefficient**
Specific gravity(G)	-0.062
Specific gravity(AD)	-0.116
Specific gravity(OD)	-0.191*
Vessel diameter (μm)	0.363**
vessel area (μm)	0.362**
vessel frequency	-0.421**
Ray height (μm)	0.161*
Ray width (μm)	0.012

Ray frequency	-0.234**
Radial shrinkage (G to AD)	-0.017
Radial shrinkage (AD to OD)	-0.101
Radial shrinkage (G to OD)	-0.089
Tangential shrinkage (G to AD)	0.044
Tangential shrinkage (AD to OD)	-0.046
Tangential shrinkage (G to OD)	-0.01
Moisture content (G)	0.140
Heartwood %	0.569*
Extractive content (%)	0.526**
Heartwood colour	-0.096
Bark thickness	-0.373

*** significant at 0.01 level; * significant at 0.05 level*

4.3 Physical Properties

4.3.1 Specific gravity

The results for specific gravity in all the three conditions (green, air dry and oven dry) shows significant variation between the samples from different locations. There exists significant difference between fast grown and slow grown samples for oven dry specific gravity. The results also point out a significant location wise variation among the samples. The specific gravity under green and air dry conditions did not show any significant variation between fast grown and slow grown samples. But both the properties showed significant difference with respect to the samples of different locations. Teak samples from Nilambur (0.92) and Tanzania (0.91) (Table 3), both belonging to the fast grown category showed no significant difference for specific gravity (green). The samples from Ghana had the lowest value (0.63), and it significantly differed from all the other samples. The samples from Vadavar (Tamil Nadu) showed the highest value of 1.17 and also it significantly differed from rest of the samples. The slow grown samples like Myanmar (0.86), Thailand (0.87), Konni (0.79), Betul (Madhya

Pradesh) (0.74), Sudan (0.91), Malayattoor (0.86) and Trinidad (0.92) didn't show any significant difference between each another with regard to green specific gravity.

Air dry specific gravity showed results similar to that of specific gravity (green). Air dry specific gravity ranged from 0.60 to 0.82. The samples from Nilambur (0.73), Ranni (0.71) and Benin (0.73) belonging to the fast grown category showed no significant difference with the slow grown teak samples from Myanmar (0.71), Thailand (0.72), Malayattoor (0.76) and Trinidad (0.69). The lowest value of air dry specific gravity was for teak samples from Ghana (0.60), and it significantly differed from all the other samples. Sudan teak showed a higher value of 0.82 which was not significantly different from Vadavar (Tamil Nadu) teak (0.81). No significant difference existed between fast grown samples from Cameroon (0.68) and Tanzania (0.67). Slow grown sample from Konni (0.64) was not significantly different from fast grown Tanzanian teak (0.67).

The specific gravity (oven dry) showed significant difference between the fast and slow grown samples ($p < 0.001$). Fast grown samples possessed 4.5 % higher value over slow grown samples for specific gravity (oven dry). The specific gravity (oven dry) ranged from 0.55 to 0.71 for fast grown samples and 0.58 to 0.67 for slow grown samples. At the same time, wood property showed significant variation between the sample locations. Highest value was obtained for Vadavar teak (Tamil Nadu) (0.71) and was not significantly different from Benin teak (0.70), where both the samples come under the fast grown category. The Nilambur sample (0.68) was not significantly different from Benin sample. The lowest value was shown by the sample from Ghana and was significantly different from all the other samples. The slow grown samples like Betul (Madhya Pradesh) (0.60), Konni (0.58), Sudan (0.60) and Trinidad (0.60) showed little variation. Samples from Thailand did not show any significant difference with sample from Myanmar (0.62) and Sudan (0.60). Among the fast grown samples, sample from Cameroon (0.62) was found to have no significant difference with Tanzanian teak (0.60) and Ranni teak (0.65).

Table 3. Variation in wood specific gravity (green, air dry and oven dry) of fast grown and slow grown teak.

Growth Rate	Location	Specific Gravity (G)**	Specific Gravity (AD)**	p value	Specific Gravity (OD)**
Fast Grown	Nilambur	0.92^{b} (0.115)	0.73^{bc} (0.014)	< 0.001	0.68^{bc} (0.033)
	Benin	0.80^{cd} (0.026)	0.73^{bc} (0.014)		0.70^{ab} (0.019)
	Ranni	0.77^{d} (0.047)	0.71^{cde} (0.034)		0.65^{cde} (0.022)
	Camaroon	0.80^{cd} (0.024)	0.68^{ef} (0.036)		0.62^{ef} (0.025)
	Ghana	0.64^{e} (0.011)	0.60^{h} (0.013)		0.55^{h} (0.003)
	Tanzania	0.92^{b} (0.119)	0.67^{fg} (0.018)		0.60^{fg} (0.015)
	Vadavar	1.17^{a} (0.024)	0.81^{a} (0.012)		0.71^{a} (0.041)
Slow Grown	Myanmar	0.86^{bc} (0.020)	0.71^{cde} (0.030)	< 0.001	0.63^{def} (0.021)
	Thailand	0.87^{bc} (0.056)	0.72^{cd} (0.017)		0.66^{cd} (0.018)
	Betul	0.74^{d} (0.061)	0.68^{ef} (0.038)		0.59^{g} (0.018)
	Konni	0.80^{cd} (0.092)	0.64^{g} (0.017)		0.58^{g} (0.011)
	Sudan	0.91^{b} (0.086)	0.82^{a} (0.026)		0.60^{fg} (0.010)
	Malayattoor	0.86^{bc} (0.051)	0.76^{b} (0.023)		0.67^{bc} (0.011)
	Trinidad	0.92^{b} (0.047)	0.69^{def} (0.021)		0.60^{fg} (0.009)

Means with the same letter are homogeneous

*** significant at 0.01 level; * significant at 0.05 level*

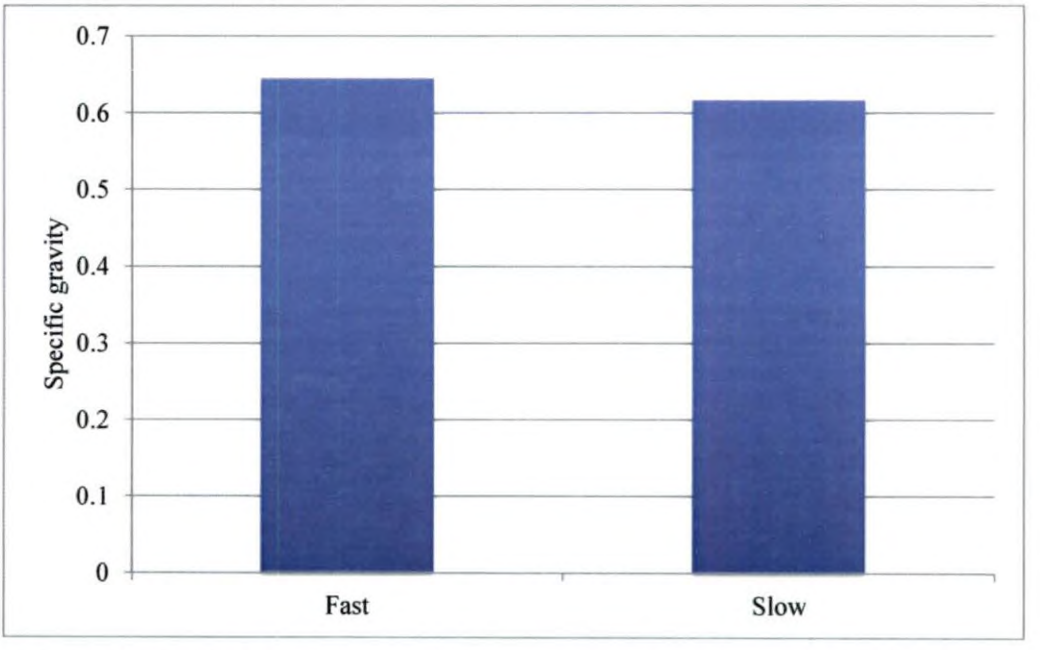


Fig 2. Variation in specific gravity of fast and slow grown teak

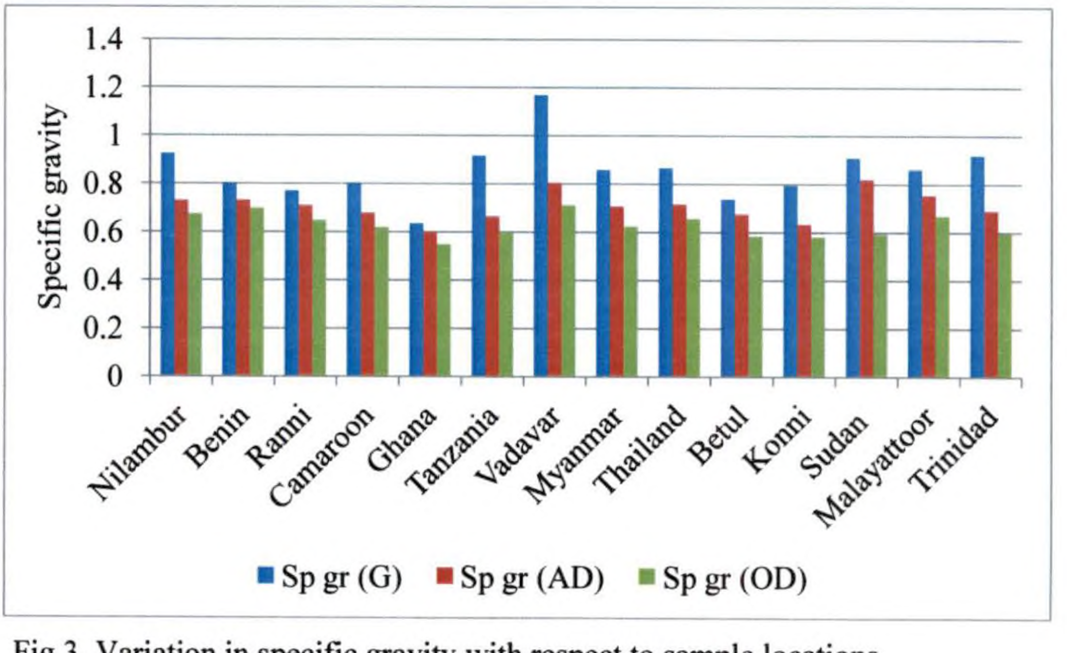


Fig 3. Variation in specific gravity with respect to sample locations

4.3.2 Shrinkage

4.3.2.1 Radial Shrinkage

4.3.2.1a Variation in radial shrinkage (green to air dry)

Radial shrinkage (green to air dry) was found to be significant between fast and slow grown samples at five percent level, but the difference between the samples based on their locations were found to be non-significant. Fast grown samples showed 15.4 % higher value for radial shrinkage (green to air dry) compared to slow grown samples (Table 4).

4.3.2.1b Variation in radial shrinkage (air dry to oven dry)

The analysis of variance showed highly significant ($p < 0.001$) values for radial shrinkage (air dry to oven dry) between fast and slow grown sample, while between the sample locations, non-significant results were obtained. Similar to the results obtained for radial shrinkage (green to air dry), for radial shrinkage (air dry to oven dry) fast grown samples (1.62 %) had higher values than the slow grown samples (1.31 %) (Table 4).

4.3.2.1c Variation in radial shrinkage (green to oven dry)

Radial shrinkage (green to oven dry) showed results identical to that of radial shrinkage (air dry to oven dry). The average shrinkage values obtained for the fast grown samples were 18 % higher than that of the slow grown samples. Faster grown samples showed a value range of 2.25 % to 3.04 %, while slow grown samples showed 2.01 % to 2.53 % values for radial shrinkage (green to oven dry) (Table 4).

Table 4. Variation in radial shrinkage of fast grown and slow grown teak

Growth Rate	Location	Radial Shrinkage					
		p value	Green to air dry^{ns}	p value	Air dry to oven dry^{ns}	p value	Green to oven dry^{ns}
Fast Grown	Nilambur	0.015	1.05 (0.289)	0.004	1.95 (0.295)	< 0.001	3.04 (0.121)
	Benin		0.96 (0.160)		1.27 (0.362)		2.26 (0.485)
	Ranni		0.88 (0.168)		1.84 (0.560)		2.74 (0.682)
	Camaroon		1.08 (0.239)		1.29 (0.319)		2.39 (0.344)
	Ghana		1.03 (0.159)		1.47 (0.634)		2.53 (0.565)
	Tanzania		0.90 (0.212)		2.07 (0.241)		3.00 (0.024)
	Vadavar		1.23 (0.268)		1.51 (0.236)		2.77 (0.178)
Slow Grown	Myanmar	0.015	0.92 (0.059)	0.004	1.07 (0.107)	< 0.001	2.01 (0.163)
	Thailand		0.96 (0.215)		1.23 (0.488)		2.22 (0.337)
	Betul		1.08 (0.411)		1.42 (0.585)		2.53 (0.337)
	Konni		0.75 (0.186)		1.44 (0.132)		2.21 (0.265)
	Sudan		0.83 (0.281)		1.37 (0.330)		2.22 (0.275)
	Malayattoor		0.74 (0.213)		1.34 (0.297)		2.09 (0.398)
	Trinidad		0.75 (0.107)		1.30 (0.181)		2.06 (0.090)

ns: non-significant

4.3.2.2 Tangential Shrinkage

4.3.2.2a Variation in tangential shrinkage (green to air dry)

The analysis of variance for tangential shrinkage (green to air dry) revealed that the difference between fast and slow grown samples with regard to this property was non-significant. Between the sample locations, there exists significant variation at five per cent level. The tangential shrinkage (green to air dry) values range from 1.71 % (Betul) to 2.76 % (Myanmar). Among the sample locations, Ranni (2.56 %) and Vadavar (Tamil Nadu) (2.65 %) were found to be significantly different from Betul (Madhya Pradesh) (1.71 %) and Tanzania (1.73 %), while Sudan (1.86 %) and Malayattoor (1.89 %) samples differed significantly from Betul (1.71 %), Myanmar (2.76 %) and Vadavar (2.65 %) (Table 5).

4.3.2.2b Variation in tangential shrinkage (air dry to oven dry)

Tangential shrinkage (air dry to oven dry) showed no significant difference in growth rates (i.e. fast and slow) of the sample as well as between locations. The average tangential shrinkage (air dry to oven dry) values of fast grown samples were found to be slightly higher (9 %) than that of the slow grown samples. The shrinkage values ranged from 2.05 % to 3.21 % (Table 5).

4.3.2.2c Variation in tangential shrinkage (green dry to oven dry)

Highly significant results were obtained for tangential shrinkage (green dry to oven dry), both between the growth rates ($p < 0.001$) of the sample and between the sample locations ($p = 0.002$). Fast grown samples were found to be having the 8 % higher average compared to slow grown samples. Among fast grown samples, the sample from Benin (5.41 %) was having the highest value for tangential shrinkage (green dry to oven dry) and was not significantly different from all the other samples in the fast grown category except Nilambur (4.60 %), which showed no difference with the slow grown samples like Thailand (4.73 %), Betul (Madhya Pradesh) (4.28%), Konni (4.66 %), Sudan (4.57 %), Malayattoor (4.19 %) and Trinidad (4.28 %). In the slow grown category, Myanmar was having the largest value (5.44 %) for tangential shrinkage (green dry to oven dry) and was found to be having 18 % larger mean than the rest of the samples in the slow grown category (Table 5).

Table 5. Variation in tangential shrinkage of fast grown and slow grown teak

Growth Rate	Location	Tangential Shrinkage			
		Green to air dry*	Air dry to oven dry^{ns}	p value	Green to oven dry**
	Nilambur	2.43^{abc} (0.287)	2.05 (0.327)		4.60^{cde} (0.056)
	Benin	2.08^{abc} (0.373)	3.21 (0.345)		5.41^{a} (0.213)
	Ranni	2.56^{ab} (0.783)	2.59 (1.255)		5.29^{ab} (0.503)
Fast Grown	Camaroon	2.19^{abc} (0.497)	2.59 (0.644)	< 0.001	4.89^{abcd} (0.820)
	Ghana	2.25^{abc} (0.472)	2.78 (0.855)		5.14^{abc} (0.536)
	Tanzania	1.73^{c} (0.105)	3.17 (0.238)		4.99^{abc} (0.290)
	Vadavar	2.65^{a} (0.421)	2.17 (0.352)		4.95^{abc} (0.112)
	Myanmar	2.76^{a} (0.283)	2.54 (0.436)		5.44^{a} (0.151)
	Thailand	2.18^{abc} (0.396)	2.45 (0.113)		4.73^{bcde} (0.509)
	Betul	1.71^{c} (0.363)	2.50 (0.531)		4.28^{de} (0.443)
Slow Grown	Konni	2.08^{abc} (0.228)	2.49 (0.263)	< 0.001	4.66^{bcde} (0.200)
	Sudan	1.86^{bc} (0.536)	2.62 (0.499)		4.57^{cde} (0.225)
	Malayattoor	1.89^{bc} (0.419)	2.22 (0.434)		4.19^{e} (0.360)
	Trinidad	2.10^{abc} (0.606)	2.09 (0.658)		4.28^{de} (0.250)

Means with the same letter are homogeneous ; ns: non-significant
*** significant at 0.01 level; * significant at 0.05 level*

4.3.2.3 Coefficient of anisotropy

Coefficient of anisotropy (the ratio of tangential to radial shrinkage) showed no significant difference between fast and slow grown samples (Table 8), but slightly greater mean was found for fast grown samples compared to slow grown. Significant location-wise difference was found with regard to the property of coefficient of anisotropy. Sample from Myanmar (2.79) and Benin (2.70) showed the highest value and was found significantly different from the samples from Nilambur (1.55), Tanzania (1.74), Vadavar (Tamil Nadu) (1.89) and Betul (Madhya Pradesh) (1.89).

Table 6. Variation in coefficient of anisotropy of fast grown and slow grown teak

Growth Rate	Location	Coefficient of anisotropy *
Fast Grown	Nilambur	1.55^{c} (0.262)
	Benin	2.70^{a} (1.069)
	Ranni	2.20^{abc} (0.940)
	Cameroon	2.42^{ab} (1.318)
	Ghana	2.37^{ab} (1.070)
	Tanzania	1.74^{bc} (0.475)
	Vadavar	1.89^{bc} (0.533)
Slow Grown	Myanmar	2.79^{a} (0.572)
	Thailand	2.16^{abc} (0.274)
	Betul	1.89^{bc} (0.797)
	Konni	2.27^{abc} (0.661)
	Sudan	2.13^{abc} (0.332)
	Malayattoor	2.22^{abc} (0.906)
	Trinidad	2.23^{abc} (0.719)

Means with the same letter are homogeneous
*** significant at 0.01 level; * significant at 0.05 level*

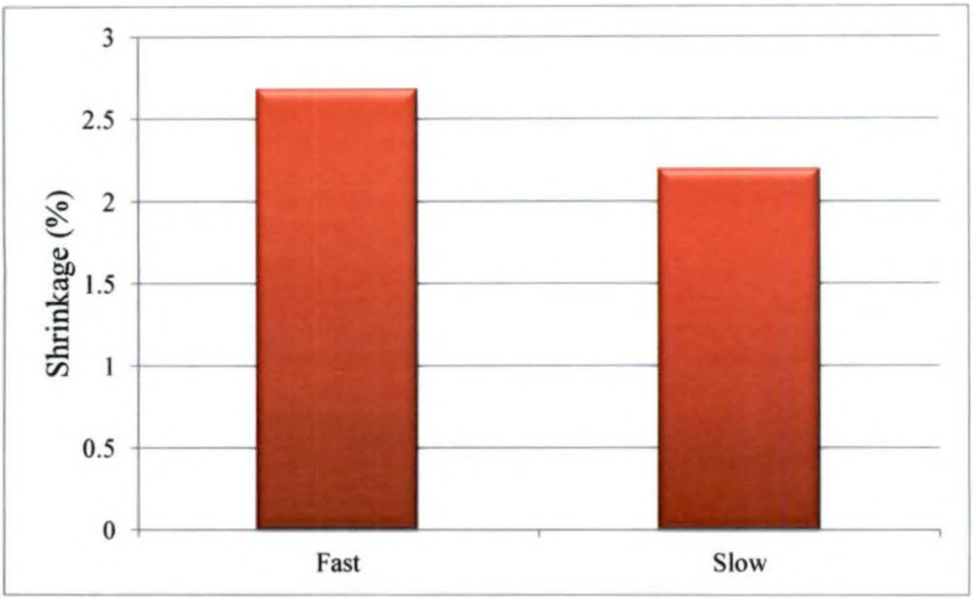


Fig 4. Variation in radial shrinkage (G-OD) of fast and slow grown teak

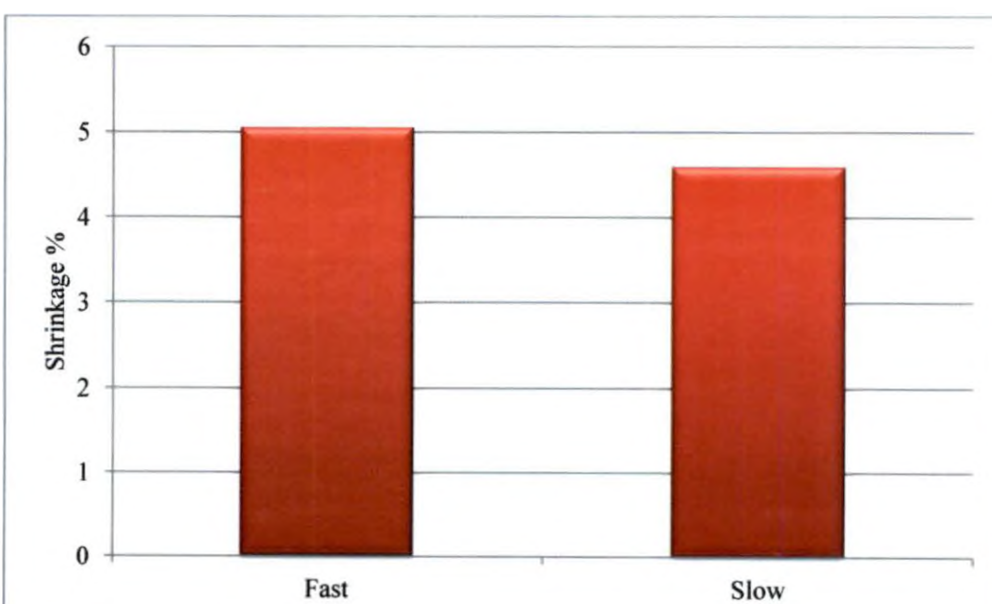


Fig 5. Variation in tangential shrinkage (G-OD) of fast and slow grown teak

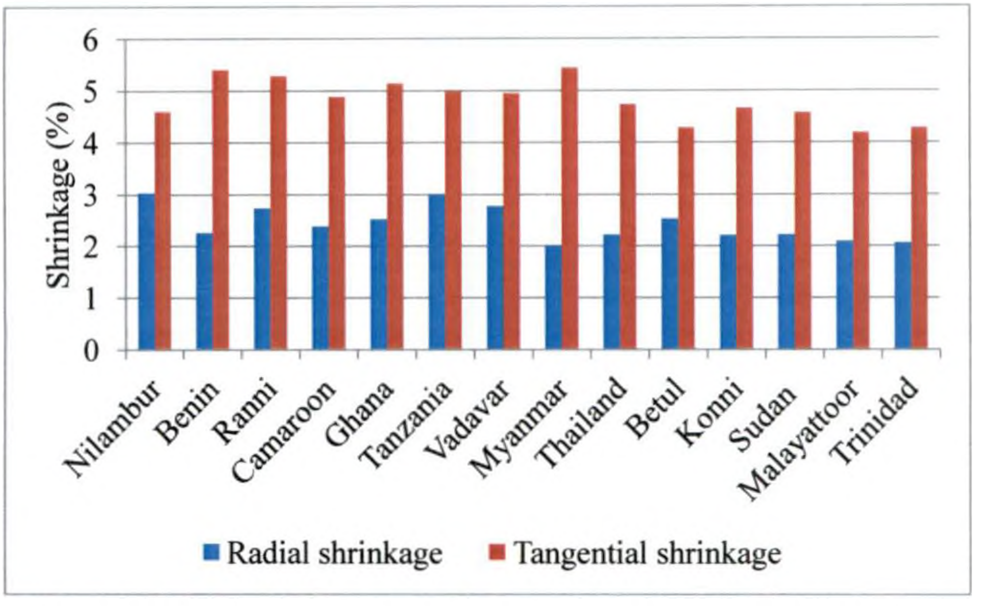


Fig 6. Variation in wood shrinkage with respect to sample locations

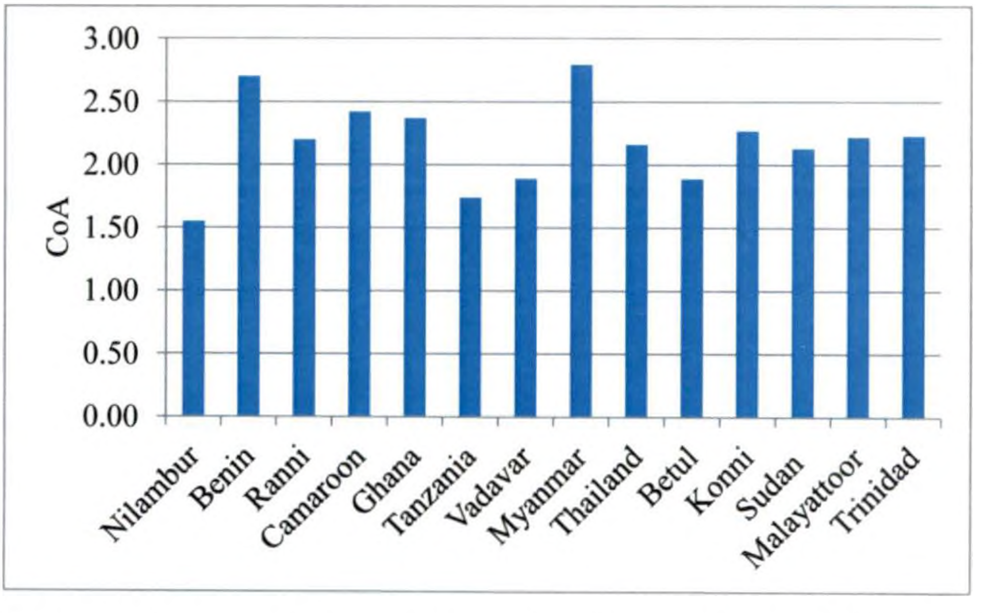


Fig 7. Variation in coefficient of anisotropy with respect to sample locations

Nilambur teak had the lowest value and it did not show significant variation from the samples from Ranni (2.20), Tanzania (1.74), Vadavar (1.89), Thailand (2.16) Betul (1.89), Konni (2.27), Sudan (2.13) and Malayattoor (2.22).

4.3.3 Moisture content

Moisture content of the sample at green and air dry conditions was studied as part of physical property analysis. Moisture content at green condition showed significant variation only with regard to sample locations ($p < 0.001$). But when the means were compared, fast grown samples showed 9 per cent higher moisture content than the slow grown samples. Among the sample locations, highest value for moisture content (green) was found for the sample from Betul (80.39%), followed by Ranni (72.54 %), Ghana (67.63 %), Nilambur (64.34 %), Vadavar (Tamil Nadu) (63.80 %), Trinidad (61.52) Tanzania (63.80 %), Malayattoor (63.80 %), Cameroon (53.75 %), Myanmar (58.88 %), Benin (53.42 %), Thailand (52.18 %), Konni (42.78 %) and Sudan (41.02 %). Sudan teak which showed the lowest moisture content, was significantly different from the samples from Betul (Madhya Pradesh), Nilambur, Ranni, Ghana and Vadavar (Tamil Nadu); whereas it showed no significant variation from rest of the samples.

Significant variation in moisture content (air dry) was observed between fast and slow grown samples, while location-wise variation was found to be non-significant. Similar to moisture content (green), higher moisture content (air dry) (15.82 %) was shown by the fast grown samples, whereas slow grown samples showed a 14 % lesser value compared to fast grown samples.

Table 7. Variation in moisture content (%) of fast grown and slow grown teak

Growth Rate	Location	Moisture Content (G)**	P value	Moisture Content % (AD)^{ns}
Fast Grown	Nilambur	64.26^{ab} (11.58)		15.70 (1.77)
	Benin	53.42^{bcd}		15.87

		(5.82)		(1.38)
	Ranni	72.54^{ab} (8.61)		16.25 (2.12)
	Cameroon	53.75^{bcd} (14.71)	< 0.001	15.36 (0.97)
	Ghana	67.63^{ab} (10.56)		17.51 (1.68)
	Tanzania	61.40^{abcd} (12.11)		14.93 (2.17)
	Vadavar	63.80^{abc} (17.29)		15.14 (1.48)
Slow Grown	Myanmar	58.88^{bcd} (15.46)	< 0.001	12.97 (3.18)
	Thailand	52.18^{bcd} (7.48)		12.31 (1.51)
	Betul	80.39^{a} (9.18)		14.36 (1.14)
	Konni	42.78^{cd} (5.76)		13.35 (1.30)
	Sudan	41.02^{d} (0.87)		14.14 (1.81)
	Malayattoor	60.59^{abcd} (26.10)		13.97 (1.07)
	Trinidad	61.52^{abcd} (10.16)		13.92 (2.67)

Means with the same letter are homogeneous; ns: non-significant
*** significant at 0.01 level; * significant at 0.05 level*

4.3.4 Heartwood percentage

The variation in heartwood percentage between fast and slow grown teak was found to be non-significant (Table 8), while higher means (about 12 % more) was found for the samples of slow grown category (79.5 %) compared to the fast grown samples (69.25 %).

Table 8. Variation in heartwood Percentage of fast grown and slow grown teak

Parameter	Growth Rate	Mean^{ns}
Heartwood %	Fast	69.29 (16.18)
	Slow	79.70 (6.43)

ns: non-significant

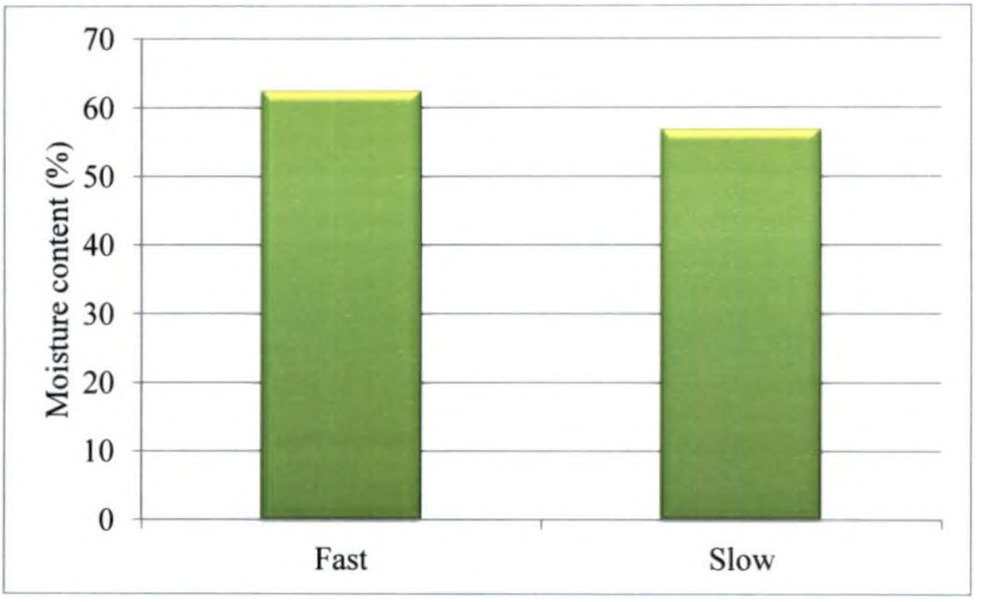


Fig 8. Variation in moisture content (green) of fast and slow grown teak

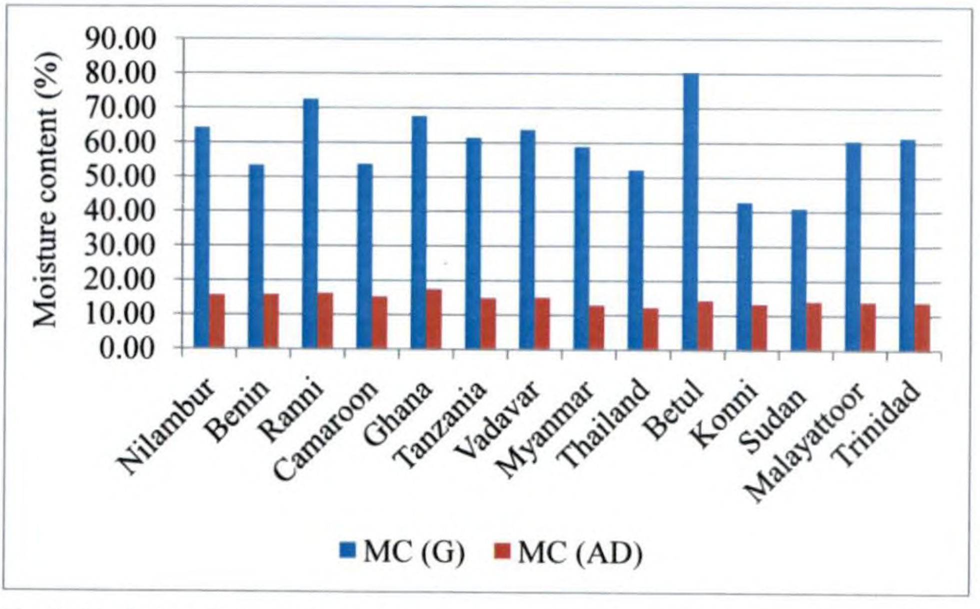


Fig 9. Variation in moisture content (green) with respect to sample locations

4.3.5 Heartwood colour

Heartwood colour determining components (hue, value and chroma) did not show any significant variation between the fast and slow grown samples (Table 9).

Table 9. Variation in heartwood colour components of fast grown and slow grown teak

Parameters		Growth Rate	Mean^{ns}
Heartwood colour	Hue	Fast	8.57 (1.34)
		Slow	9.29 (1.22)
	Value	Fast	5.29 (0.76)
		Slow	5.00 (0.58)
	Chroma	Fast	5.71 (1.38)
		Slow	6.00 (1.63)

ns: non-significant

The variations in colour with respect to the samples of different locations are given in the table 10. Among the teak samples of 14 different localities, a total of six colour variations were described with the help of Munsell system (i.e. brown, dark brown, brownish yellow, strong brown, yellow and yellowish brown). Four samples (Myanmar, Thailand, Sudan and Trinidad) were found to be having yellowish brown heartwood. Brownish yellow heartwood was observed for the samples from Benin, Cameroon and Malayattoor. The samples from Nilambur and Betul (Madhya Pradesh) showed brown colour; Ranni and Konni had dark brown colour; Ghana and Tanzania showed strong brown and the Vadavar (Tamil Nadu) sample was found to be having yellow heartwood colour.

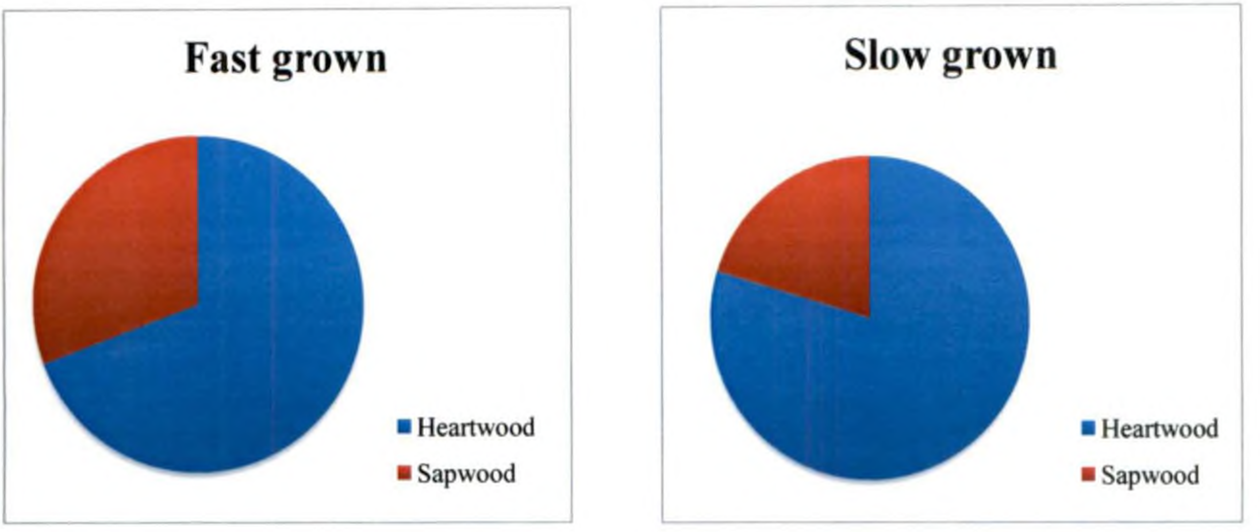


Fig 10. Variation in heartwood percentage of fast and slow grown teak

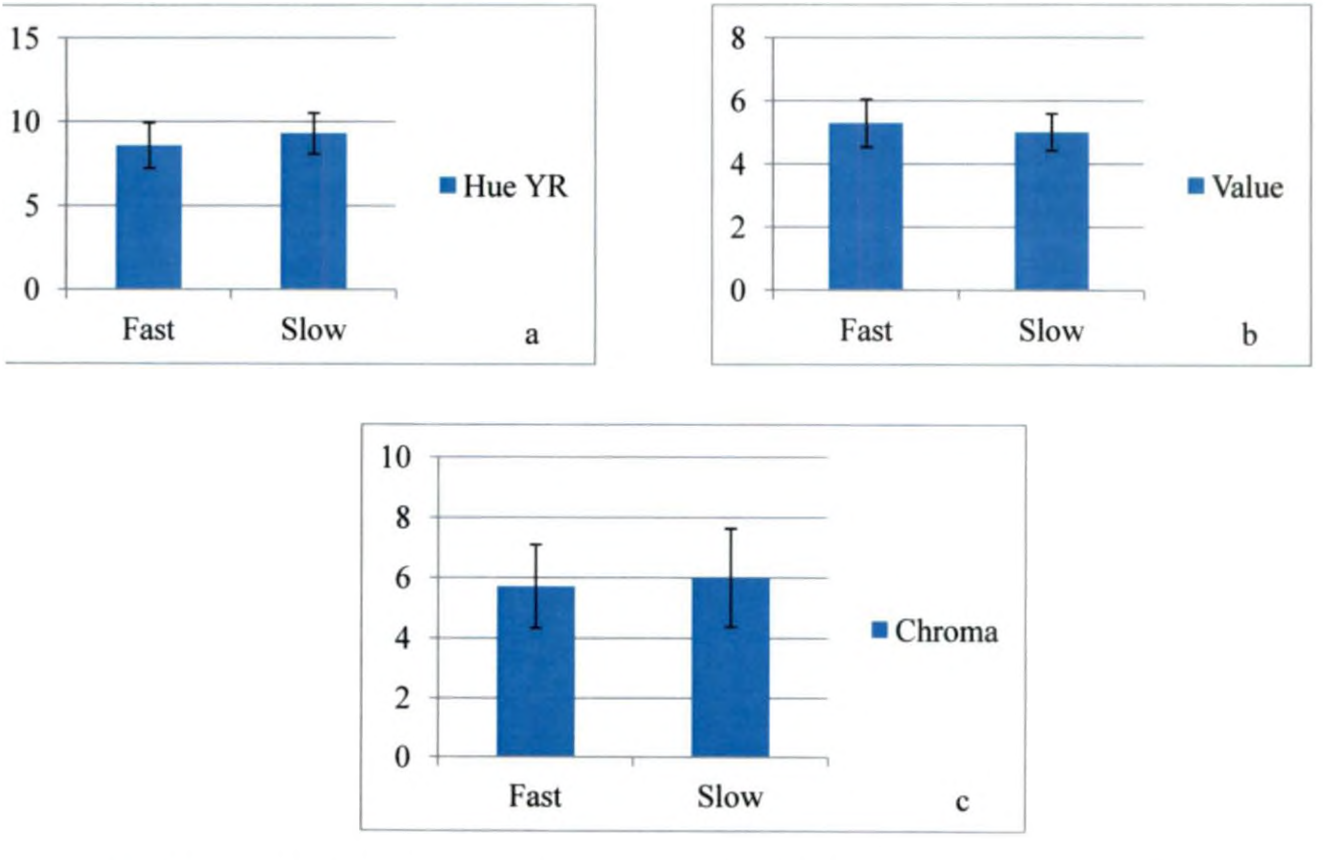


Fig 11(a-c). Variation in heartwood colour components of fast and slow grown teak

Table 10. Variation in heartwood colour with respect to sample locations

Location	Munsell system			Colour description	
	Hue	Value	Chroma		
Nilambur	7.5	5	4	7.5YR/5/4	Brown
Benin	10	6	6	10YR/6/6	Brownish yellow
Ranni	7.5	4	4	7.5YR/4/4	Dark brown
Cameroon	10	6	8	10YR/6/8	Brownish yellow
Ghana	7.5	5	6	7.5YR/5/6	Strong brown
Tanzania	7.5	5	6	7.5YR/5/6	Strong brown
Vadavar	10	7	6	10YR/7/6	Yellow
Myanmar	10	5	6	10YR/5/6	Yellowish brown
Thailand	10	5	6	10YR/5/6	Yellowish brown
Betul	7.5	5	4	7.5YR/5/4	Brown
Konni	7.5	4	4	7.5YR/4/4	Dark brown
Sudan	10	5	8	10YR/5/8	Yellowish brown
Malayattoor	10	6	6	10YR/6/6	Brownish yellow
Trinidad	10	5	8	10YR/5/8	Yellowish brown

4.3.6 Bark thickness

The t-test revealed no significant difference between the samples of fast and slow grown categories with regard to bark thickness (Table 11). Though the results were non-significant, the faster grown samples showed a higher mean (5.91 mm) for bark thickness than the slow grown samples (3.97 mm)

Table 11. Variation in bark thickness of fast grown and slow grown teak

Parameters	Growth Rate	Mean^{ns}
Bark thickness (mm)	Fast	5.91 (1.63)
	Slow	3.97 (1.56)

ns: non-significant

4.4 Anatomical Properties

4.4.1 Vessel Morphology

The results of vessel diameter were found to be highly significant between fast and slow grown samples (Table 12). The slow grown teak samples showed a 9.1% higher mean vessel diameter than the fast grown samples. Vessel diameter values ranged from 205.5 μm to 265.7 μm for fast grown samples, while it showed higher value range of 143.7 μm to 342.9 μm for the slow grown samples. Vessel diameter also showed significant variation among the sample locations. The highest vessel diameter was found for Myanmar teak (342.92 μm) and was having a 58 % higher value than the Thailand teak (143.67 μm) which was having the lowest value for vessel diameter. Both Myanmar and Thailand samples, which were categorised under the slow grown list, were found to be significantly different from all the other samples. The fast grown samples showed lesser variability for vessel diameter. The samples viz. Nilambur (206.02 μm), Ranni (212.08 μm), Cameroon (205.50 μm), Tanzania (221.67 μm), Vadavar (Tamil Nadu) (223.33), Ghana (230.42 μm) and Benin (265.68 μm) showed no significant difference between each other. Among slow grown samples except Myanmar and Thailand, all other samples showed no significant difference for vessel diameter. The slow grown samples like Trinidad (258.67 μm), Malayattoor (222.82 μm), Sudan (233.25 μm) and Betul (Madhya Pradesh) (237.75 μm) did not show any significant difference with the fast grown samples from Nilambur (206.02), Ranni (212.08 μm), Cameroon (205.50 μm), Tanzania (221.67 μm), Vadavar (223.33 μm) and Ghana (230.42 μm).

Vessel area was found to have significant variation between the fast and slow grown samples. A 17.9 % lower mean vessel area was found for fast grown samples compared to slow grown. The analysis also revealed high significant variation in vessel area between the samples of different localities ($p < 0.001$). Similar to the results for vessel diameter, the highest vessel area was shown by the Myanmar sample (117653.6 μm^2), which was not significantly different from the samples from Konni (88583.4 μm^2) and the lowest value was obtained for Thailand (28504.0 μm^2), which was found to be significantly different from rest of the samples. Fast grown samples like Vadavar (Tamil Nadu) (58794.3 μm^2), Tanzania (58536.2 μm^2) and Ghana (58226.7 μm^2) did not show any significant difference between Nilambur (50746.6 μm^2), Ranni (49657.3 μm^2), Cameroon (44985.7 μm^2), and Benin (81446.4 μm^2) and also they were found to be homogenous with the slow grown samples like Betul (Madhya Pradesh) (61932.5 μm^2), Sudan (62112.3 μm^2), Malayattoor (57890.0 μm^2) and Trinidad (73909.7 μm^2) with regard to vessel area (Table 12).

The results for vessel frequency revealed that there was no significant difference between the fast and slow grown samples. On the other hand, vessel frequency showed significant variation between teak samples of different locations ($p < 0.001$). The vessel frequency value for the studied samples ranged from 3 to 9. The lowest value was observed for the sample from Myanmar (3/mm^2) and was found to have no significant difference with the Nilambur sample which possessed 4 vessels per millimetre square. The highest vessel frequency was observed for the teak sample from Malayattoor (9/mm^2) and was not significantly different from the Vadavar and Tanzania samples where each of these samples had the vessel frequency value of 8 per mm^2. The Vadavar (Tamil Nadu) and Tanzania samples were found to be statistically similar to the samples viz. Ghana, Ranni, Sudan and Trinidad, each with 7 vessels per mm^2. Remaining samples such as Konni, Betul (Madhya Pradesh), Thailand, Cameroon and Benin had vessel frequency value as 6/mm^2 and were at par (Table 12).

Table 12. Variation in vessel parameters of fast grown and slow grown teak

Growth Rate	Location	p value	Vessel Diameter** (µm)	p value	Vessel Area** (logarithmic Transformed ± SD)	Vessel Frequency** (No./mm^2)
Fast Grown	Nilambur	< 0.001	206.02^{e} (19.875)	0.018	50746.6^{d} (10.84 ± 0.109)	4^{e} (0.380)
	Benin		265.68^{bc} (17.835)		81446.4^{bc} (11.31 ± 0.059)	6^{cd} (1.354)
	Ranni		212.08^{e} (32.362)		49657.3^{d} (10.81 ± 0.276)	7^{bcd} (1.268)
	Cameroon		205.50^{e} (37.233)		44985.7^{d} (10.71 ± 0.325)	6^{d} (0.809)
	Ghana		230.42^{cde} (28.036)		58226.7^{cd} (10.97 ± 0.287)	7^{bcd} (0.776)
	Tanzania		221.67^{de} (34.512)		58536.2^{cd} (10.98 ± 0.273)	8^{ab} (1.015)
	Vadavar		223.33^{de} (20.201)		58794.3^{cd} (10.98 ± 0.174)	8^{ab} (0.280)
Slow Grown	Myanmar	< 0.001	342.92^{a} (25.651)	0.018	117653.6^{a} (11.68 ± 0.176)	3^{e} (0.710)
	Thailand		143.67^{f} (18.990)		28504.0^{e} (10.26 ± 0.219)	6^{cd} (0.927)
	Betul		237.75^{cde} (22.482)		61932.5^{cd} (11.03 ± 0.227)	6^{cd} (0.843)
	Konni		282.75^{b} (44.251)		88583.4^{ab} (11.39 ± 0.317)	6^{d} (0.581)
	Sudan		233.25^{cde} (20.313)		62112.3^{cd} (11.04 ± 0.217)	7^{bc} (0.699)
	Malayattoor		222.82^{de} (28.889)		57890.0^{cd} (10.97 ± 0.221)	9^{a} (0.576)
	Trinidad		258.67^{bcd} (26.070)		73909.7^{bc} (11.21 ± 0.294)	7^{bcd} (0.941)

Means with the same letter are homogeneous
*** significant at 0.01 level; * significant at 0.05 level*

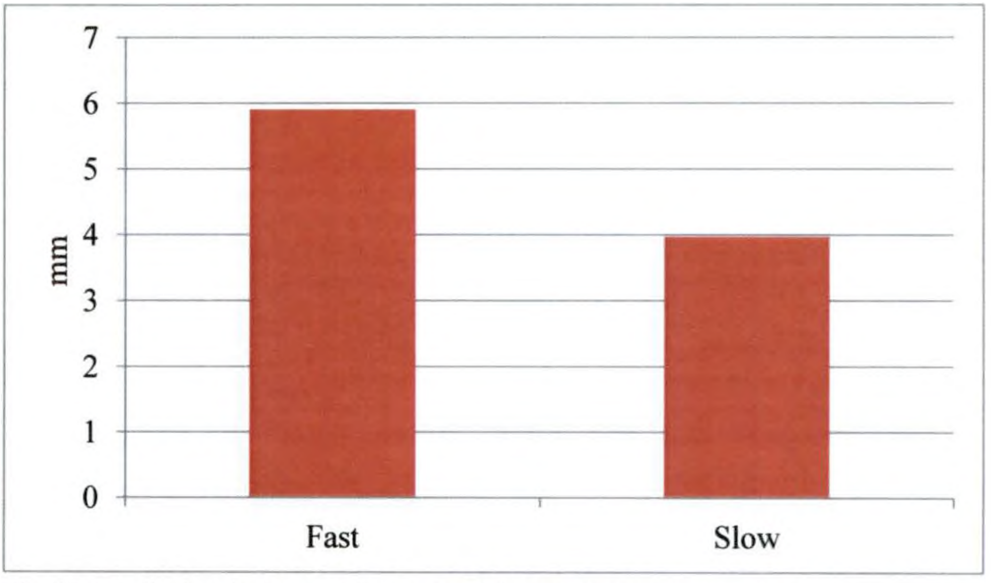


Fig 12. Variation in bark thickness of fast and slow grown teak

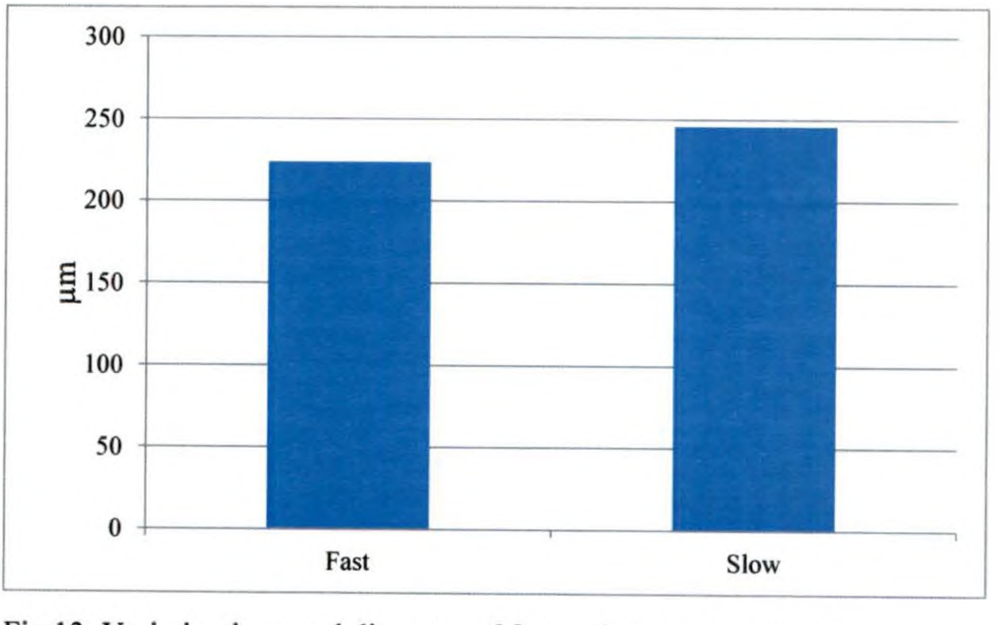


Fig 13. Variation in vessel diameter of fast and slow grown teak

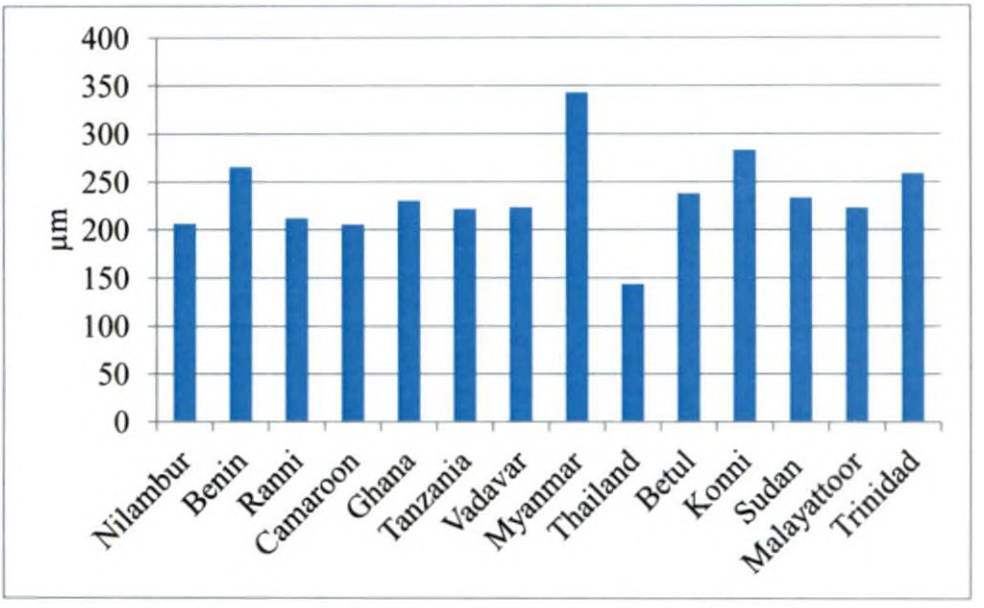


Fig 14. Variation in vessel diameter with respect to sample locations

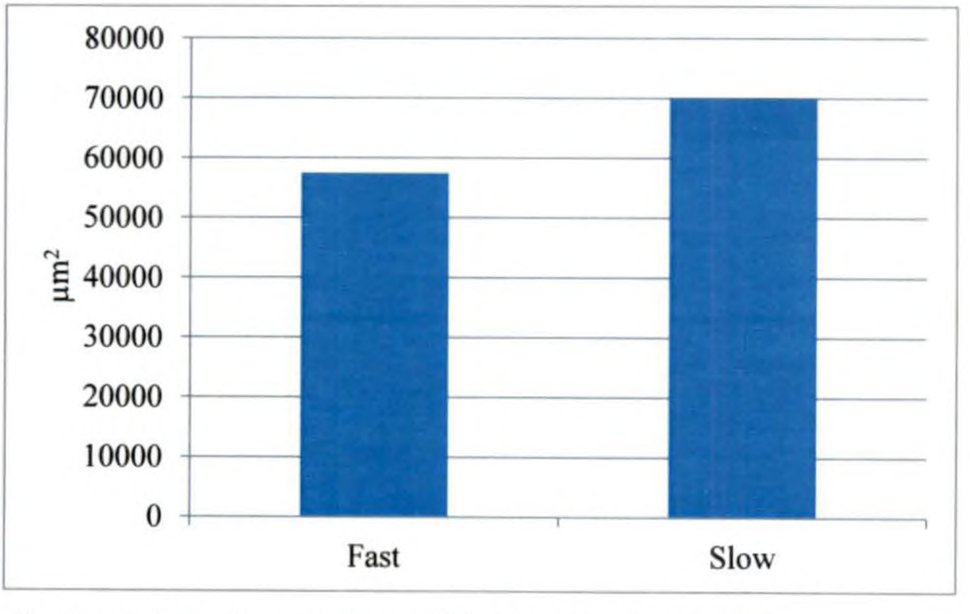


Fig 15. Variation in vessel area of fast and slow grown teak

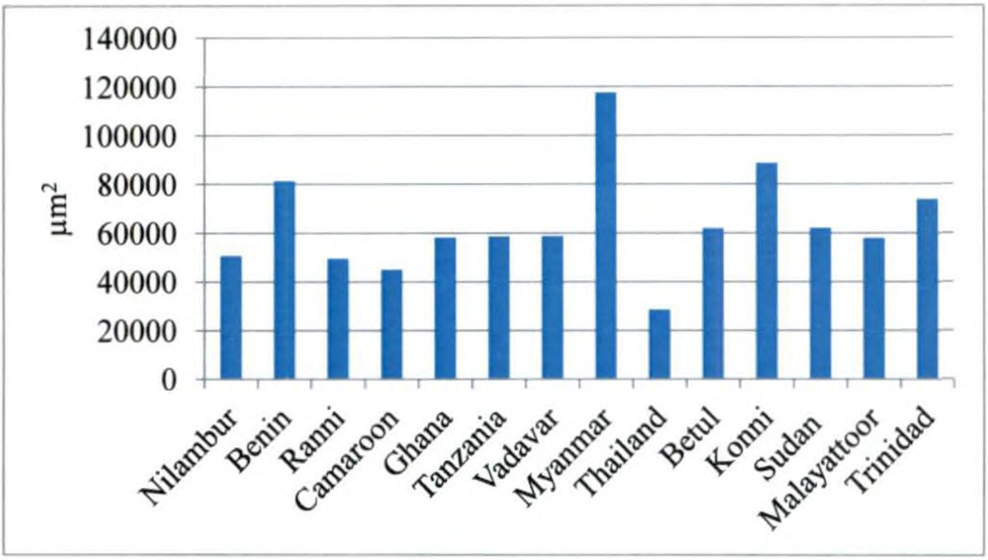


Fig 16. Variation in vessel area with respect to sample locations

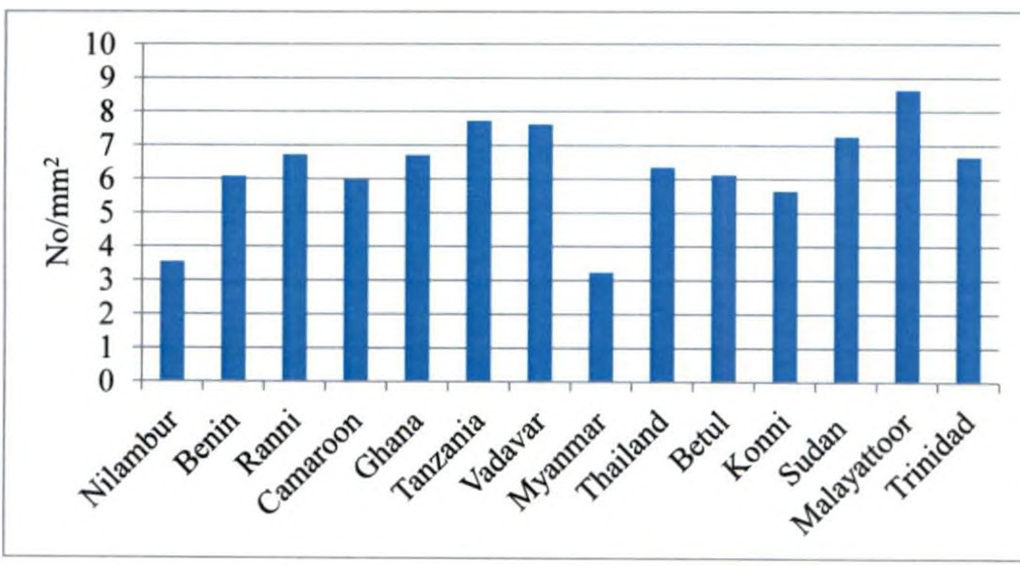


Fig 17. Variation in vessel frequency with respect to sample locations

4.4.2 Ray Morphology

Ray height was found to be significantly influenced by the rate of growth and location of the sample. The slow grown samples showed 11.8 % larger mean ray height compared to fast grown samples. Ray height values ranged from 645.5 μm to 1065.23 μm for slow grown samples and of 542.75 μm to 717.17 μm for fast grown samples. The highest ray height was observed for the Konni teak (1065.23 μm) and was significantly different from all the other samples. Konni teak showed 34 % higher ray height compared to rest of the samples in the slow grown category. Nilambur teak showed the lowest ray height and was having 24% lower ray height compared to slow grown samples. Nilambur sample was found to be significantly different from the fast grown samples such as Benin (703.33 μm), Cameroon (645.58 μm), Ghana (680.27 μm) and Vadavar (717.17 μm) (Table 13), but didn't show any significant difference with the samples from Ranni (554.42 μm), and Tanzania (606.25 μm) belonging to the fast grown category.

Ray width showed significant variation between the fast and slow grown samples at five percent level, while locality wise variation was observed at one percent level of significance. Ray width had 6 % higher values for the slow grown samples than the fast grown samples. Among the sample locations, fast grown samples such as Nilambur (48.83 μm), Benin (47.16 μm), Ranni (44.75 μm) and Myanmar (47.41 μm) didn't show any significant difference between the samples from Tanzania, Betul, Sudan, Malayattoor, and Trinidad, where excluding Tanzania, rest belonging to the samples of slow grown category. Konni teak with a ray width value of 96 μm had the highest ray width among all the samples and was found to be significantly different from all the other samples. The fast grown samples like Ghana and Vadavar did not show significant differences between each other in the case of ray width, also the samples from Thailand and Cameroon were found to be homogeneous.

Table 13. Variation in ray parameters of fast grown and slow grown teak

Growth Rate	Location	p value	Ray Height** (µm)	p value	Ray Width** (µm)	Ray Frequency** (No./mm^2)
Fast Grown	Nilambur	< 0.001	542.75^{e} (58.023)	0.017	48.83^{de} (7.333)	4^{g} (0.707)
	Benin		703.33^{bc} (81.910)		47.16^{de} (3.313)	4^{fg} (1.071)
	Ranni		554.42^{de} (72.652)		44.75^{de} (4.099)	9^{ab} (0.684)
	Camaroon		645.58^{bcd} (51.751)		80.08^{b} (3.096)	7^{de} (0.480)
	Ghana		680.27^{bc} (72.943)		65.83^{c} (3.160)	7^{d} (0.652)
	Tanzania		606.25^{cde} (27.517)		42.00^{e} (2.007)	9^{a} (0.878)
	Vadavar		717.17^{b} (61.915)		64.33^{c} (7.239)	8^{cd} (0.747)
Slow Grown	Myanmar	< 0.001	665.17^{bc} (8.104)	0.017	47.41^{de} (5.028)	5^{fg} (0.716)
	Thailand		668.92^{bc} (100.440)		77.75^{b} (10.162)	5^{fg} (0.903)
	Betul		680.75^{bc} (23.635)		40.75^{e} (1.849)	7^{d} (0.892)
	Konni		1065.23^{a} (129.266)		96.01^{a} (15.404)	5^{ef} (0.417)
	Sudan		645.50^{bcd} (29.854)		52.42^{d} (5.452)	7^{cd} (0.528)
	Malayattoor		669.67^{bc} (50.022)		52.67^{d} (2.545)	8^{abc} (1.763)
	Trinidad		649.08^{bc} (62.929)		52.42^{d} (3.192)	8^{bcd} (1.136)

Means with the same letter are homogeneous
*** significant at 0.01 level; * significant at 0.05 level*

The variation in ray frequency between the fast and slow grown was found to be non-significant, but there exists a highly significant difference between the sample locations at one percent level of significance. The number of rays per millimetre was found to be varying from 4 to 9 rays per mm^2. The samples which were having minimum ray frequency include Nilambur ($4/mm^2$), Benin ($4/mm^2$) and Myanmar ($5/mm^2$), Thailand ($5/mm^2$). These mentioned samples were found to be significantly different from the homogeneous sets of samples from Cameroon ($7/mm^2$), Ghana ($7/mm^2$), Vadavar (Tamil Nadu) ($8/mm^2$), Betul (Madhya Pradesh) ($7/mm^2$), Sudan ($7/mm^2$), Malayattoor ($8/mm^2$) and Trinidad ($8/mm^2$).

4.5 Biochemical properties

4.5.1 Extractive content analysis

Variation in extractive content (%) was found to be highly significant ($p < 0.001$) with respect to sample growth rate and location of the sample (Table 14). The slow grown samples showed 22 % higher extractive content than that in fast grown samples. Fast grown samples were found to be having a mean value of 7.17 %, while a higher mean of 9.21 % was shown by slow grown samples. Location wise variation was also found to be highly significant in the case of extractive content. The samples from Konni (11.13 %) showed the highest value and it showed no significant difference with the sample locations, Betul (10.44 %), Trinidad (10.19 %) and Myanmar (9.64 %). The samples from Malayattoor (9.22 %) showed homogeneity with Thailand (8.81 %), Nilambur (8.05 %), Cameroon (7.82 %), and Vadavar (7.47 %). Among the samples, lowest value was shown by the teak samples from Sudan (5.02 %) and it was found to be homogeneous with the fast grown samples such as Ranni (6.21 %), Benin (6.61 %), Ghana (6.89 %), Tanzania (7.13 %), Vadavar (7.47 %) and Cameroon (7.82 %).

Table 14. Variation in extractive content (%) of fast grown and slow grown teak

Growth Rate	Location	P value	Extractive Content %**
Fast Grown	Nilambur	< 0.001	8.053^{cdef} (1.328)
	Benin		6.607^{fg} (0.319)
	Ranni		6.205^{fg} (0.682)
	Cameroon		7.817^{cdef} (0.500)
	Ghana		6.885^{f} (1.039)
	Tanzania		7.132^{ef} (0.181)
	Vadavar		7.472^{def} (2.357)
Slow Grown	Myanmar	< 0.001	9.643^{abc} (1.570)
	Thailand		8.807^{bcde} (0.280)
	Betul		10.437^{ab} (0.300)
	Konni		11.133^{a} (0.401)
	Sudan		5.022^{g} (0.654)
	Malayattoor		9.218^{bcd} (0.780)
	Trinidad		10.190^{ab} (0.785)

Means with the same letter are homogeneous
*** significant at 0.01 level; * significant at 0.05 level*

5.1 Interrelationship between wood properties

5.1.1 Specific gravity Vs Anatomical properties

Correlation analysis showed weak correlations between specific gravity and different anatomical properties. Ray width was found to be slightly negatively correlated to specific gravity (air dry). There exists significant

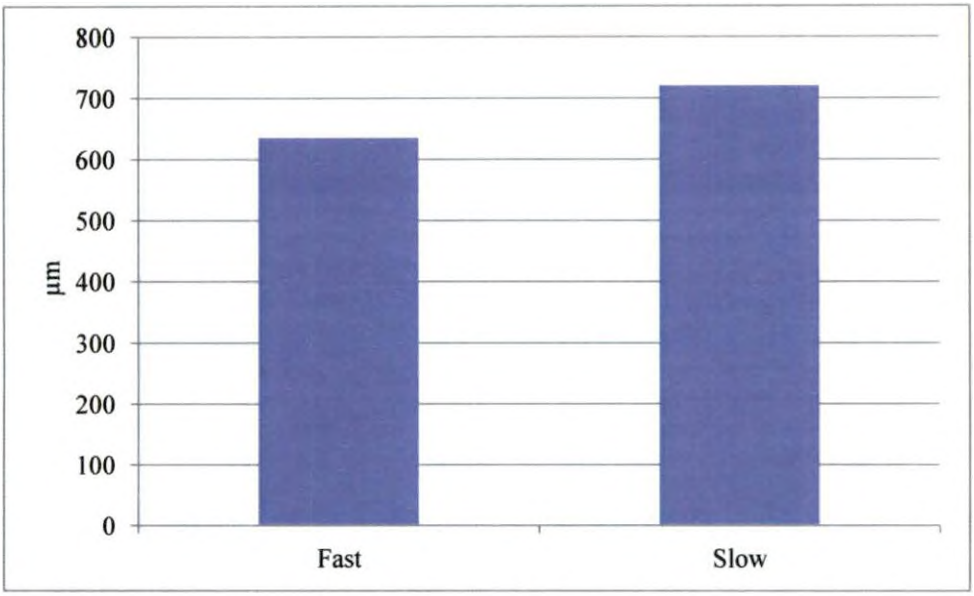


Fig 18. Variation in ray height of fast and slow grown teak

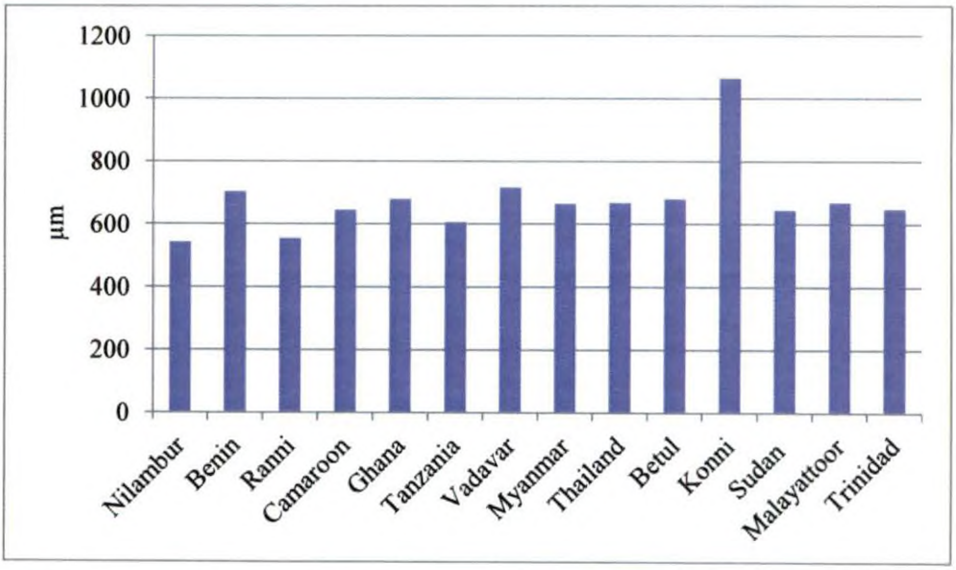


Fig 19. Variation in ray height with respect to sample locations

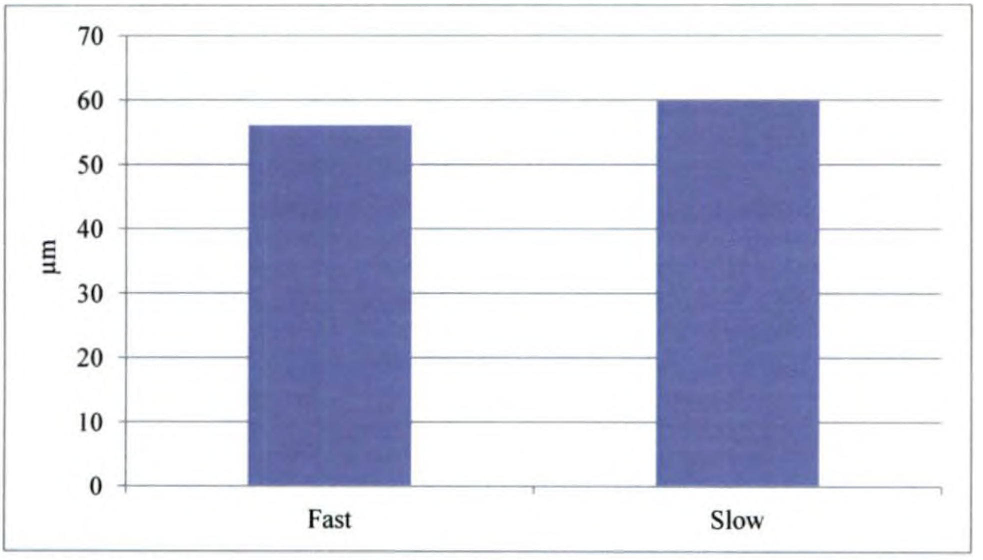


Fig 20. Variation in ray width of fast and slow grown teak

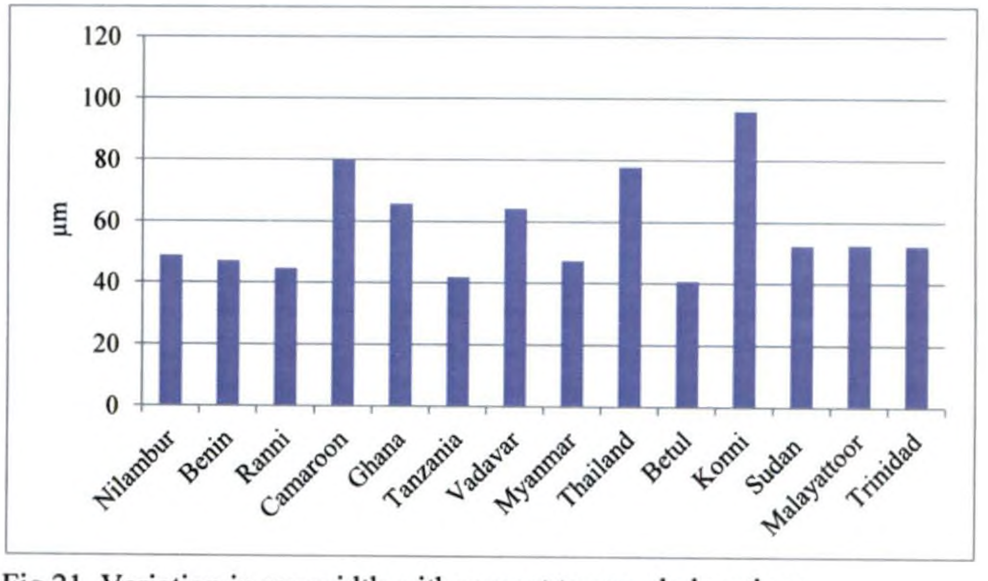


Fig 21. Variation in ray width with respect to sample locations

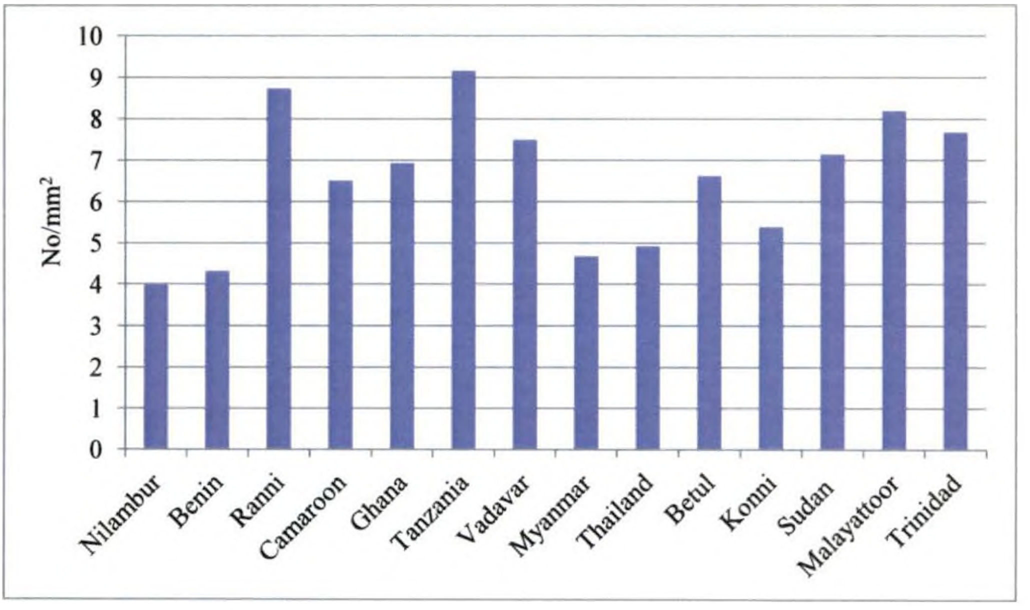


Fig 22. Variation in ray frequency with respect to sample locations

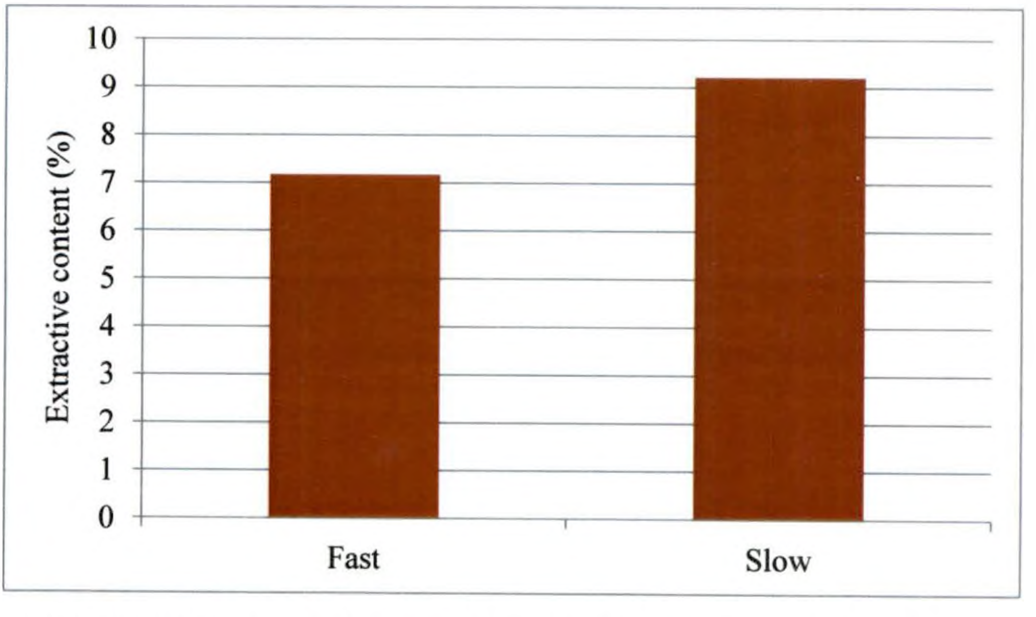


Fig 23. Variation in extractive content (%) of fast and slow grown teak

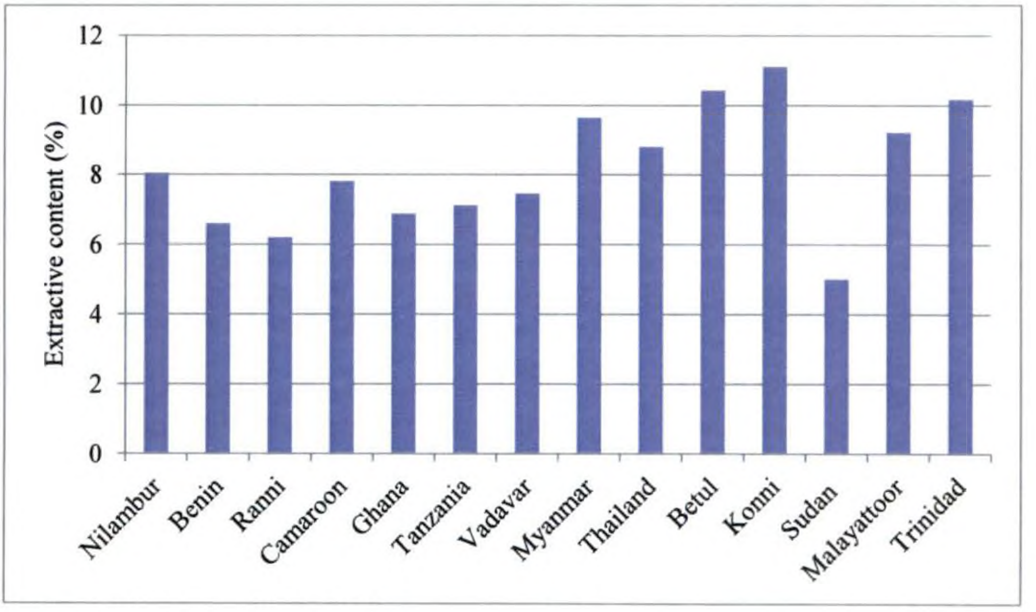


Fig 24. Variation in extractive content (%) with respect to sample locations

correlation between specific gravity at green, air dry and oven dry conditions. Specific gravity (green) showed moderate, positive correlation with air dry specific gravity (0.577) and oven dry specific gravity (0.410); similarly air dry specific gravity was found to be positively correlated with oven dry specific gravity (0.553). Among anatomical properties, vessel area and vessel diameter showed significant positive correlation with a correlation coefficient of 0.873, while both vessel area and vessel diameter was found to be having significant negative correlation with vessel frequency (Table 15). A positive and significantly higher correlation was found between the properties ray height and ray width (0.720) at 1 per cent level of significance.

5.1.2 Specific gravity Vs Physical properties

The results on correlation of physical properties like shrinkage and moisture content with specific gravity was found to be non-significant. But other physical properties such as extractive content (percentage) and hue (red to yellowness) value of heartwood colour showed significant correlation with specific gravity (Table 16). Extractive content (percentage) was found to be negatively correlated to air dry specific gravity (-0.312), where as hue value was found to have significant positive correlation with air dry specific gravity (0.596) and oven dry specific gravity (0.578).

5.1.3 Shrinkage Vs Moisture Content

Radial shrinkage at air dry to oven dry and green to oven dry conditions showed significant positive correlation with moisture content on air dry basis (Table 17). Significant positive high level correlation (0.823) was found between air dry to oven dry radial shrinkage and green to oven dry radial shrinkage; similarly, tangential shrinkage at air dry to oven dry and green to oven dry conditions also showed significant positive correlation (0.556), but significant negative correlation was found between green to air dry tangential shrinkage and air dry to oven dry tangential shrinkage.

5.1.4 Shrinkage Vs Anatomical properties

Results on correlation analysis are shown in the table 18. Green to oven dry tangential shrinkage shows a weak but significant positive correlation (0.160) with vessel diameter. No other significant correlation was found between the shrinkage and anatomical properties.

5.1.5 Shrinkage Vs other physical properties

The physical properties such as heartwood percentage and extractive content analysis were found to have significant correlation with green to oven dry tangential shrinkage. Heartwood percentage showed significant negative correlation (-0.591) with green to oven dry tangential shrinkage at 5 per cent level (Table 19), while extractive content (%) showed a weak but negative correlation (-0.395) at 1 per cent level of significance.

5.1.6 Anatomical properties Vs other physical properties

The ray height was found to have significant positive correlation with the value (0.56) and chroma (0.61) components of heartwood colour (Table 20). The components value (0.65) and chroma (0.73) also showed significant positive correlation with hue, which is the third colour component.

Table 15. Correlation between specific gravity and anatomical properties

Parameters	SG (G)	SG (AD)	SG (OD)	VD	VA	VF	RH	RW	RF
SG (G)	1.000								
SG (AD)	.577**	1.000							
SG (OD)	.410**	.553**	1.000						
VD	-0.007	-0.057	-0.081	1.000					
VA	-0.006	-0.108	-0.092	.873**	1.000				
VF	0.114	0.097	0.060	-.196**	-.232**	1.000			
RH	-0.058	-0.085	-0.059	0.075	0.086	-0.015	1.000		
RW	-0.085	-.154*	-0.114	-0.077	-0.083	-0.003	.720**	1.000	
RF	0.049	-0.007	-0.062	0.042	-0.025	0.135	-0.109	-0.124	1.000

**significant at 1 % level; *significant at 5 % level; others are non-significant

Where: SG (G) – Specific gravity (green); SG (AD) – Specific gravity (air dry); SG (OD) – Specific gravity (oven dry); VD – Vessel diameter; VA – Vessel area; VF – Vessel frequency; RH – Ray height, RW – Ray width, RF – Ray frequency

Table 16. Correlation between specific gravity and other physical properties

Parameters	SG (G)	SG (AD)	SG (OD)	HW%	EC (%)	Hue	Value	Chroma	BT
SG (G)	1.000								
SG (AD)	.577**	1.000							
SG (OD)	.410**	.553**	1.000						
HW %	0.377	0.076	-0.025	1.000					
EC (%)	-0.050	-.312*	-0.107	.645*	1.000				
Hue	0.355	.596*	.578*	0.169	-0.012	1.000			
Value	0.170	0.148	0.265	0.110	-0.037	.645*	1.000		
Chroma	0.126	0.337	0.260	0.145	-0.257	.733**	0.499	1.000	
BT	0.140	0.329	0.295	-0.241	-0.165	0.014	-0.083	-0.342	1.000

**significant at 1 % level; *significant at 5 % level; others are non-significant

Where: SG (G) – Specific gravity (green); SG (AD) – Specific gravity (air dry); SG (OD) – Specific gravity (oven dry); HW % - Heartwood percentage; EC (%) – Extractive content percentage; BT – Bark thickness

Table 17. Correlation between shrinkage and moisture content

Parametrs	RS (G to A)	RS (A to O)	RS (G to O)	TS (G to A)	TS (A to O)	TS (G to O)	MC (AD)	MC (G)
RS (G to A)	1.000							
RS (A to O)	-.275**	1.000						
RS (G to O)	.320**	.823**	1.000					
TS (G to A)	-0.019	-0.012	-0.024	1.000				
TS (A to O)	0.108	0.023	0.087	-.662**	1.000			
TS (G to O)	0.120	0.016	0.087	.254**	.556**	1.000		
MC (AD)	0.024	.176*	.188*	0.121	-0.096	0.011	1.000	
MC (G)	0.012	-0.002	0.006	0.073	-0.059	0.006	.186*	1.000

**significant at 1 % level; *significant at 5 % level; others are non-significant

Where: RS (G to A) – Radial shrinkage (green to air dry); RS (A to O) – Radial shrinkage (air dry to oven dry); RS (G to O) – Radial shrinkage (green to oven dry); TS (G to A) – Tangential shrinkage (green to air dry); TS (A to O) – Tangential shrinkage (air dry to oven dry); TS (G to O) – Tangential shrinkage (green to oven dry); MC (AD) – Moisture content (air dry); MC (G) – Moisture content (green)

Table 18. Correlation between shrinkage and anatomical properties

Parameters	VD	VA	VF	RH	RW	RF	RS (G to A)	RS (A to O)	RS (G to O)	TS (G to A)	TS (A to O)	TS (G to O)
VD	1.000											
VA	.873**	1.000										
VF	-.196**	-.232**	1.000									
RH	0.075	0.086	-0.015	1.000								
RW	-0.077	-0.083	-0.003	.720**	1.000							
RF	0.042	-0.025	0.135	-0.109	-0.124	1.000						
RS (G to A)	0.040	-0.007	-0.112	0.101	0.103	-0.045	1.000					
RS (A to O)	-0.098	-0.050	0.008	-0.101	-0.098	0.008	-.275**	1.000				
RS (G to O)	-0.073	-0.053	-0.058	-0.040	-0.036	-0.019	.320**	.823**	1.000			
TS (G to A)	0.056	0.076	-0.098	-0.070	0.040	-0.002	-0.019	-0.012	-0.024	1.000		
TS (A to O)	0.075	0.043	-0.006	0.098	-0.020	-0.076	0.108	0.023	0.087	-.662**	1.000	
TS (G to O)	.160*	0.140	-0.118	0.049	0.019	-0.101	0.120	0.016	0.087	.254**	.556**	1.000

**significant at 1 % level; *significant at 5 % level; others are non-significant

Where: VD – Vessel diameter; VA – Vessel area; VF – Vessel frequency; RH – Ray height, RW – Ray width, RF – Ray frequencyRS (G to A) – Radial shrinkage (green to air dry); RS (A to O) – Radial shrinkage (air dry to oven dry); RS (G to O) – Radial shrinkage (green to oven dry); TS (G to A) – Tangential shrinkage (green to air dry); TS (A to O) – Tangential shrinkage (air dry to oven dry); TS (G to O) – Tangential shrinkage (green to oven dry)

Table 20. Correlation between anatomical properties and other physical properties

Parameters	VD	VA	VF	RH	RW	RF	HW%	EC (%)	Hue	Value	Chroma	BT
VD	1.000											
VA	.873**	1.000										
VF	-.196**	-.232**	1.000									
RH	0.075	0.086	-0.015	1.000								
RW	-0.077	-0.083	-0.003	.720**	1.000							
RF	0.042	-0.025	0.135	-0.109	-0.124	1.000						
HW %	0.058	0.050	0.221	0.501	0.044	0.185	1.000					
EC (%)	0.010	0.134	-0.042	0.198	0.069	0.021	.645*	1.000				
Hue	0.091	-0.003	0.149	0.461	0.310	0.046	0.169	-0.012	1.000			
Value	-0.030	-0.104	0.032	.563*	0.313	0.399	0.110	-0.037	.645*	1.000		
Chroma	0.130	-0.019	0.261	.605*	0.428	0.112	0.145	-0.257	.733**	0.499	1.000	
BT	-0.507	-0.433	-0.226	-0.129	0.261	-0.321	-0.241	-0.165	0.014	-0.083	-0.342	1.000

**significant at 1 % level; *significant at 5 % level; others are non-significant

Where: VD – Vessel diameter; VA – Vessel area; VF – Vessel frequency; RH – Ray height, RW – Ray width, RF – Ray frequency; HW % - Heartwood percentage; EC (%) – Extractive content percentage; BT – Bark thickness

Table 19. Correlation between shrinkage and other physical properties

Parametrs	RS (G to A)	RS (A to O)	RS (G to O)	TS (G to A)	TS (A to O)	TS (G to O)	HW%	EC (%)	Hue	Value	Chroma	BT
RS (G to A)	1.000											
RS (A to O)	-.275**	1.000										
RS (G to O)	.320**	.823**	1.000									
TS (G to A)	-0.019	-0.012	-0.024	1.000								
TS (A to O)	0.108	0.023	0.087	-.662**	1.000							
TS (G to O)	0.120	0.016	0.087	.254**	.556**	1.000						
HW%	-0.267	0.280	0.140	-0.296	-0.070	-.591*	1.000					
EC (%)	-0.251	0.026	-0.119	-0.226	-0.043	-.395**	.645*	1.000				
Hue	-0.074	-0.088	-0.131	0.267	-0.480	-0.394	0.169	-0.012	1.000			
Value	0.117	0.048	0.111	-0.001	-0.126	-0.234	0.110	-0.037	.645*	1.000		
Chroma	-0.058	0.019	-0.017	-0.109	-0.084	-0.349	0.145	-0.257	.733**	0.499	1.000	
BT	-0.204	0.055	-0.059	0.417	-0.331	0.143	-0.241	-0.165	0.014	-0.083	-0.342	1.000

**significant at 1 % level; *significant at 5 % level; others are non-significant

Where: RS (G to A) – Radial shrinkage (green to air dry); RS (A to O) – Radial shrinkage (air dry to oven dry); RS (G to O) – Radial shrinkage (green to oven dry); TS (G to A) – Tangential shrinkage (green to air dry); TS (A to O) – Tangential shrinkage (air dry to oven dry); TS (G to O) – Tangential shrinkage (green to oven dry); HW % - Heartwood percentage; EC (%) – Extractive content percentage; BT – Bark thickness

Table 20. Correlation between anatomical properties and other physical properties

Parameters	VD	VA	VF	RH	RW	RF	HW%	EC (%)	Hue	Value	Chroma	BT
VD	1.000											
VA	.873**	1.000										
VF	-.196**	-.232**	1.000									
RH	0.075	0.086	-0.015	1.000								
RW	-0.077	-0.083	-0.003	.720**	1.000							
RF	0.042	-0.025	0.135	-0.109	-0.124	1.000						
HW %	0.058	0.050	0.221	0.501	0.044	0.185	1.000					
EC (%)	0.010	0.134	-0.042	0.198	0.069	0.021	.645*	1.000				
Hue	0.091	-0.003	0.149	0.461	0.310	0.046	0.169	-0.012	1.000			
Value	-0.030	-0.104	0.032	.563*	0.313	0.399	0.110	-0.037	.645*	1.000		
Chroma	0.130	-0.019	0.261	.605*	0.428	0.112	0.145	-0.257	.733**	0.499	1.000	
BT	-0.507	-0.433	-0.226	-0.129	0.261	-0.321	-0.241	-0.165	0.014	-0.083	-0.342	1.000

**significant at 1 % level; *significant at 5 % level; others are non-significant

Where: VD – Vessel diameter; VA – Vessel area; VF – Vessel frequency; RH – Ray height, RW – Ray width, RF – Ray frequency; HW % - Heartwood percentage; EC (%) – Extractive content percentage; BT – Bark thickness

Nilambur

Ranni

Konni

Malayattoor

Vadavar (Tamil Nadu)

Betul (Madhya Pradesh)

Plate 10a. Cross sectional discs of teak obtained from different locations within India

Myanmar

Thailand

Tanzania

Cameroon

Ghana

Benin

Sudan

Trinidad and Tobago

Plate 10b. Cross sectional discs of teak obtained from different locations outside India

DISCUSSION

DISCUSSION

The variation in wood physical, anatomical and biochemical properties of teak samples studied as part of the investigation on effect of rate of growth on different wood quality of teak with special reference to the teak samples, which were grown within the country as well as from outside are discussed hereunder.

5.1 Ring width analysis

The present study categorises the samples from Kerala (except Malayatoor and Konni) and Tamil Nadu as fast grown (i. e. ≥ 5 mm) on the basis of average ring width. This observation is in conformity with the study conducted by Indira et al. (2010). The highest value for average ring width was shown by Vadavar Teak (Tamil Nadu) followed by Ghana, Nilambur, Ranni, Tanzania, Benin and Camaroon. Bhat and Priya (2004) also reported higher ring width for teak from fast growing locations of Nilambur. The lower radial growth of Konni teak compared to the Nilambur teak was also observed in a study conducted by Bhat and Indira (1997). The fast rate of growth of Tanzanian teak was reported by Malande and Temu (1990). Since the growth rate can be easily assessed based on the ring width, in this study average ring width was chosen as a parameter to categorise the samples from of locations.

5.2 Effect of age

The study found very low correlation between age of the samples and the wood quality determining parameters (viz. physical, anatomical and biochemical properties). Several studies have reported similar results in case of different wood properties in teak and also in other species. Wanneng (2011) in his study on wood property assessment of teak plantation of different ages grown in Lao PDR also reported a poor relationship between wood properties and sample age. In Togolese teak Kokutse et al. (2004) reported that wood density or wood specific gravity do not differ significantly with age after reaching the age of 40-45 years. Bhat (1995) found that 51 year old tree possess only 5 percent higher wood density than that of 8 year old tree growing in the same region. In *Swietenia* *macrophylla*, Ashaduzzaman et al. (2011) reported a poor correlation between tree age and wood density in air dry condition. The same study showed a significant effect of age on density in the other two conditions (i. e. green and oven dry), which was contradictory with the results of the present study. The properties like vessel diameter, vessel area and vessel frequency were found to be having a weak correlation with age. Similar results were reported by Bhat (1998), in which it was found that after 25 years of age, vessel diameter will be stable throughout the life time and thereafter age has little effect on vessel diameter. The same study also reported a minimum influence of age on ray morphology and specific gravity.

In the present study, properties like moisture content and shrinkage did not show any significant correlation with the sample age. This result was in conformity with the result obtained by Ashaduzzaman et al. (2011) in *Swietenia macrophylla* for properties like average moisture content and radial shrinkage. Though heartwood percentage and extractive content showed significant positive correlation with sample age, the correlation coefficient denoted a low or moderate value of 0.569 and 0.526, the former at five per cent level and the latter at one per cent level of significance. Therefore, in the present study, the variation in wood properties seems to be more dependent on other factors (viz. growth rate, locality) than sample age, which may be attributed to the high amount of mature wood present in the collected samples.

5.3 Physical properties

5.3.1 Specific gravity

The specific gravity (green, air dry and oven dry) obtained in the study was within a value range of 0.64 to 1.17, 0.60 to 0.82 and 0.55 to 0.71 respectively. This was in conformity with the values reported by Jayawardana and Amarasekera (2009) for plantation grown teak in Sri Lanka. The specific gravity values were also comparable with the values observed for the same by Richter et al. (2003) in plantation grown Ghana teak and values are slightly higher than those reported by Bhat (1998) in fast and slow grown samples from Nilambur, Konni, Peechi, Walayar and Arayankavu.

The present study shows a significant difference between fast and slow grown samples for specific gravity (oven dry) i. e. a 4.5 per cent higher value for fast grown samples over the slow grown samples. The observation is in tune with the earlier observations made by Scot and Mac Gregor (1952) in teak that, faster growing tree have a slightly higher specific gravity. In *Swietenia macrophylla*, Briscoe et al. (1963) found that specific gravity increases with growth rate. Bhat et al. (1998) also suggested that fast grown teak was not necessarily less dense and lighter. Furthermore, Jayawardana and Amarasekera (2009) reported that, there is little relationship between specific gravity and growth rate and also the fast growth rate in shorter rotations was unlikely to reduce specific gravity in teak. But contradictory to the present study results, Bhat and Priya (2004) reported a slightly lower specific gravity for fast grown Nilambur teak compared to slow grown teak from Konni and North Kanara. Bhat et al. (2005) reported no significant specific gravity differences between wet and dry teak despite the faster growth of teak in the wet condition. The higher specific gravity for fast grown samples compared to slow grown samples in the present study might be attributed to the presence of high percentage of mature wood characterised by lower presence of parenchyma tissues and lower vessel diameter in the fast grown samples.

The specific gravity in all the three conditions shows significant location wise variation among the samples. This reveals the need to consider the role of geographical sites/locations when explaining the results on the physical properties of teak. In the present study the samples from Vadavar (Tamil Nadu) and Benin showed higher specific gravity. Also, the Nilambur sample did not show any significant difference with Benin sample. The sample from Ghana which had the lowest value was significantly different from all the other samples. Slow grown samples like Betul (Madhya Pradesh), Konni, Sudan and Trinidad showed little variation between each other. The slow grown samples from Thailand, Myanmar and Sudan were all at par. Ghana teak showed a lower specific gravity compared to Myanmar teak, which supports the earlier findings of Richter et al. 2003 where a 5% lower timber density was observed for Ghana teak compared to Myanmar teak. The sample from Cameroon was found to be having no significant difference with Tanzanian teak and Ranni teak for this property. Similarly, Smeathers (1951) observed that the timber produced in plantations from Trinidad was not inferior in mechanical properties to that of Myanmar, regardless of the growth rate. The same study also revealed that Myanmar provenances planted in Trinidad developed trees with lower specific gravity than the already existing plantations in Trinidad. The mechanical properties of 51-year-old Tanzania-grown teak were found to be 15 per cent inferior to teak wood of the same age tested from Myanmar and Trinidad (Bryce, 1966). But the specific gravity observations analysed in the present study showed no significant variation between the samples from Myanmar, Tanzania and Trinidad. The present study results were contradictory to the findings of Sallenave (1958), that teak wood from West Africa were harder and heavier than teak from Asia. This may be mainly due to the variation in edaphic factors prevailing in particular localities from which the samples were obtained.

According to Tewari (1992), teak exhibits wide geographic variation in India with regard to wood figure and strength properties. Similarly, considerable amount of variation was shown by the different samples collected from India with regard to the specific gravity. The highest value for oven dry specific gravity reported for teak from Vadavar (Tamil Nadu) and was followed by those from Nilambur. The samples from Malayattoor and Ranni showed little difference with Nilambur teak, while the sample from Konni had the least specific gravity and was also significantly different from all the other samples from South India. Konni sample were not significantly different with the sample from Betul (Madhya Pradesh). The possible reason behind the higher specific gravity in the mentioned samples might be due to the greater cell wall percentage, lower vessel dimensions and also higher proportion of parenchyma possibly being related to the variability in edaphic factors in the growing localities.

5.3.2 Wood Shrinkage

The percentage wood shrinkage in radial as well as the tangential direction at green to air dry, air dry to oven dry and green to oven dry conditions were also measured. However, in this study radial shrinkage variation with regard to the geographic locations was found to be non-significant at all the three conditions. But significant variation in radial shrinkage was found between the fast and slow grown samples; the radial shrinkage (green to air dry) showed significant variation at 5 per cent level while the other two showed significant variation at 1 percent level of significance. The tangential shrinkage (green to air dry) and (air dry to oven dry) did not show any significant difference between the fast grown and slow grown samples, while tangential shrinkage (green to oven dry) showed significant difference between the fast and slow grown samples ($p < 0.001$). Tangential shrinkage at green to air dry and green to oven dry conditions however showed significant variation among the sample locations.

The shrinkage values obtained in the study were closer to those reported by Miranda et al. (2011) for teak of east Timor, wherein it was observed to be 3.50 % percent radial shrinkage and 5.17 % for tangential shrinkage. Gerhards (1964) reported 4 % radial shrinkage and 6 % tangential shrinkage for Nepal alder (*Alnus nepalensis*) and it was compared with the red alder which was having a radial and tangential shrinkage of 4.4 % and 7.3 % rspectively. Shrinkage values of 4.14 % (radial) and 7.13 % (tangential) were observed for Athel wood (*Tamarix aphlylla*) grown in Iran, but a lower radial shrinkage of 3.2 % and higher tangential shrinkage values were recorded for the same species grown at Greece (Sadegh et al., 2011), thus unlike the present study, radial shrinkage showed a significant region wise variation in Athel wood. In the present study, fast grown samples showed larger shrinkage than the slow grown samples, (i.e. 18 % for radial and 8 % for tangential) (Table 4; Table 5). Nasroun and Al-Shahrani (1998) explained the role of larger vessel diameter and ray dimensions on the wood shrinkage in five locally grown wood species of Saudi Arabia. The same study reported a positive correlation between vessel diameter and shrinkage. But in the present study the mean vessel diameter and ray height were found to be lower for the fast grown samples compared to that of slow grown samples whereas significantly higher specific gravity was found for the fast grown samples. Since a significantly higher specific gravity may add up to higher shrinkage values, the factors behind the greater shrinkage values of the fast grown over the slow grown samples might be the combined effect of relatively larger range of vessel and ray dimensions and higher specific gravity of the fast grown samples. Similar observations on the effect of specific gravity over shrinkage were reported by Sahu (2005) in *Albizia odoratissima* and by Kord et al. (2010) in *Populus euramericana*.

The tangential shrinkage at two conditions viz. green to air dry ($p = 0.035$) and green to oven dry ($p = 0.002$) showed significant variation with regard to the sample locations. Highest tangential shrinkage was shown by teak from Myanmar, followed by Benin and both showed no significant difference with the samples from Ranni, Cameroon, Ghana, Tanzania, and Vadavar (Tamil Nadu). The remaining samples which were characterized with a 13 % lower tangential shrinkage than the above mentioned samples were found to be homogeneous with regard to tangential shrinkage. This variation may be attributed to the larger amount of wood substance and also due to the variation in growing conditions of the respective samples. Similar variations have been obtained from the study conducted on Athel wood (*Tamarix aphlylla*) grown in Iran and Greece (Sadegh et al., 2011). Elzaki and Khider (2013) for *Cupressus lusitanica* wood grown in Sudan reported 5.80 % and 8.20 % as the values for tangential and volumetric shrinkage, while Moya and Munoz (2010) reported 23 per cent higher value for tangential and 11 per cent higher value for volumetric shrinkage for the same species grown in Costa Rica.

In the present study, coefficient of anisotropy (the ratio of tangential to radial shrinkage) is found to be small i.e. 1.55 for Nilambur teak followed by the samples from Tanzania, Vadavar (Tamil Nadu) and Betul (Madhya Pradesh), which indicates a low risk of deformation in wood during drying (Rijsdijk and

Laming, 1994). Miranda et al. (2011) also reported similar results for teak from East Timor. Results from the present study for shrinkage, supports the earlier findings on the superiority of Nilambur teak with respect to timber quality (Bhat and Priya, 2004), (Balasundaram et al., 2010).

5.3.3 Moisture content

Wood moisture content percentage analysed in the present study were found to be close to that reported by Sekhar et al. 1988 for Malabar and Coimbatore teak. In the present study, moisture content at green condition did not show any significant difference between fast and slow grown samples, while significant difference was found between the sample locations. Variation in air dry moisture content between fast and slow grown samples were found to be significant, but little difference was found among the samples of different locations. This difference in moisture content might be attributed to the amount of wood substance present in the studied samples. Zobel et al. (1968) observed a negative correlation between specific gravity and moisture content, therefore higher the specific gravity, lower the moisture content in wood.

5.3.4 Heartwood percentage

The heartwood proportion, which is the naturally durable part of the timber for which teak was well known, is an important factor determining wood quality. In the present study, heartwood percentage showed little difference between fast and slow grown samples. Heartwood accounted for a mean value of 69.2 % in fast and 79.5 % in slow grown samples (Table 8). Similar to the present results, Bhat et al. (2004) observed no significant variation in heartwood percentage between the teak samples from wet (fast grown) and dry (slow grown) localities, and was convincingly supported by the finding that, heartwood content vary more with respect to tree age than growth rate and locality (Bhat, 2000). The present study also showed a significant but moderate positive correlation (at 5 percent level of significance) between heartwood percentage and age of the sample (Table 2). Miranda et al. (2011) reported a heartwood proportion of 84.3

% in slow grown (i.e. of average ring width < 5 mm) teak trees of East Timor (Indonesia). The results of the present study was also in accordance with the findings of Bhat (1995) that after reaching maturity, fast grown trees could produce timber with higher proportion of heartwood, by disapproving the general notion that faster grown trees always produce higher sapwood content.

5.3.5 Heartwood colour

The mean colour values determined through Munsell system is presented in table 8. In the present study the Munsell notations for fast grown samples were comparable with slow grown samples with regard to hue (redness to yellowness), value (lightness) and chroma (saturation). Similarly, Bhat et al. (2004) and Thulasidas et al. (2006) observed no significant difference in hue and value for wet and dry teak, while the results were contradictory to the findings of Tadashi et al. (2003) and Derkyi et al. (2009) where they reported darker wood in wet area compared to teak from drier areas. The variability in luminance (i.e. darkness or lightness) is considered as the primary cause of heartwood colour variability (Phelps et al., 1983). All the samples in the present study were found to be having a red colour, tending more towards yellow-red in Munsell system. Minemura et al. (1998) reported similar tendency in 60 Malaysian timbers with respect to heartwood colour.

Wood colour as determined by Munsell notation, varied among the sample locations from yellow to yellowish brown or even darker brownish yellow and also brown to dark and strong brown (Table 10). Teak is a premium hardwood valued for its attractiveness with golden brown colour. Wood samples collected from different localities for the present study showed high variation with regard to heartwood colour. Fast grown samples from Nilambur and the slow grown sample from Betul (Madhya Pradesh) showed brown colour. Similar observations were found for teak from central India (Chattisgarh and Madhya Pradesh) by Indira et al. (2010). The samples from Vadavar (Tamil Nadu), Thailand, Myanmar, Trinidad and Sudan were yellow to yellowish brown in colour. High variability in heartwood colour was displayed by the samples from Asia compared to those from Africa. For example except the sample from Sudan, all the other samples of African origin were found to be of darker colour, while Asian teak which include the samples from teak homelands viz. India (consisting of samples from six different localities), Thailand and Myanmar showed varying degrees of paler as well as darker heartwood colour irrespective of growth rate of the samples. These variations in wood colour justifies the findings of Kaosa-ard (1995) who demonstrated the profound influence of planting locations on wood colour and texture in teak. The heartwood colour difference could also be due to variation in percentage of extractive content in wood. The same is evident from table 10 that, the samples which possessed high extractive content had displayed darker heartwood colour. At the same time, earlier studies revealed that within a species, wood colour vary greatly due to different environmental conditions and silvicultural treatments (Sullivan, 1967; Nelson et al., 1969; Wilkins and Stamp, 1990). Derkyi et al. (2009) reported that wood colour of teak was significantly associated with soil properties and was independent from the effect of tree age. Still the exact cause of such variation is not known but is possibly due to differences in soil chemistry and moisture content in different localities.

5.3.6 Bark thickness

Bark thickness is influenced by the species category, rate of growth, the genetic constitution of each tree, and position along the bole (Laasasenaho et al., 2005). Brack et al. (1985) observed higher bark thickness for slower grown trees than fast grown since the faster growing trees shed more bark. A similar trend was reported by Cellini et al. (2012), whereas Bhat et al. (2004) reported 63 per cent thicker bark for teak trees grown in wet locality (fast grown) compared to those grown in dry localities (slow grown). Contradictory to the above findings, the present study, showed no significant difference between fast and slow grown samples, while a slightly higher mean was found for fast grown samples with regard to bark thickness. This deviation might be attributed by the variation in the genetic constitution and growing locations.

5.4 Anatomical properties

5.4.1 Vessel morphology

Vessel parameters like vessel diameter, vessel area and vessel frequency were also studied as part of the present study. The results for vessel diameter was found to be significantly different between the fast and slow grown samples and it also showed significant variation among the sample locations. A value range of 143.67 μm to 342.92 μm was observed for vessel diameter which was closer to the values reported for teak by Tripati et al. (2013). When comparing the mean vessel diameter of fast and slow grown samples, a 9.1 % higher vessel diameter was observed for slow grown samples. Bhat et al. (2004) pointed out little significant difference between teak from wet (which usually considered as fast grown) and dry conditions (slow grown) with regard to vessel diameter. In *Eucalyptus grandis* Bamber et al. (1982) reported a lower vessel diameter for fast grown compared to normally grown samples. Among the sample locations, Myanmar teak (slow grown) was found to be having the largest vessel diameter (33 % higher), while Thailand teak (slow grown) had the least value. Indira et al. (2010) reported lower vessel diameter in slow grown Dandeli teak which is in support of the result for Thailand teak, while contradictory to the studies conducted by Bhat et al. (2004) and Bamber et al. (1982). In this study, the samples from Konni, Benin and Trinidad showed larger vessel diameter (269.03 μm) after Myanmar. The remaining samples showed homogeneity with regard to the vessel diameter.

Vessel area also showed significant variation between the fast and slow grown samples at 5 % level and even larger significant difference was found between the sample locations ($p < 0.001$). Similar to the results on vessel diameter, higher vessel area value was obtained for the sample from Myanmar and the sample from Thailand had the lowest vessel area among the sample locations. Vessels in trees with high growth stresses (slow grown) were larger and more frequent, compared to the low-stressed trees, thus increasing vessel volume (Malan and Gerischer, 1987). Irrigation was found to increase vessel diameter (February et al., 2005). The expected reason behind relatively higher vessel dimensions in some of the samples might be due to the variation in juvenile wood-mature wood proportion. It can be also due to the growth stresses developed as a result of management practices.

The variation in vessel frequency between the fast and slow grown samples was found to be non-significant, but there exists a highly significant difference ($p < 0.001$) between sample locations. Similar results were reported by Downes et al. (1997) with regard to fast and slow grown samples of *Eucalyptus grandis*. Bhat and Priya (2004) reported no significant difference between fast and slow grown samples with regard to vessel percentage in teak. The vessel frequency values for the studied samples ranged from 3 to 9. The lowest value was observed for the sample from Myanmar and was found to have no significant difference with the Nilambur sample. The highest vessel frequency was observed for the teak sample from Malayattoor.

5.4.2 Ray morphology

Ray width (554 µm to 1065 µm) and ray height (40 µm to 96 µm) value ranges are closer to those reported by Rehman et al. (2003) and Tripati et al. (2013) for teak. But the present study on distribution and dimensions of ray cells showed contradictory results. Ray height was found to have significant variation between the fast and slow grown samples. Slow grown samples possessed 11.8 % larger ray height compared to fast samples, also ray width shows 6 % larger average for slow grown samples than fast grown ones. These observations were contradictory to the findings of Taylor, (1969) that specific gravity increased with proportion of ray tissue in hardwoods. Bhat et al. (2001) reported that the fast grown trees contained significantly larger ray percentage than slow grown (20.3 vs. 18.7 %). Ray frequency results showed no significant variation between the fast and slow grown samples, which was similar to the observation of Rehman et al. (2003) on teak, that there was little effect of ring width on ray frequency. The same study pointed out that; there was no relationship between ring width (growth rate parameter) and average ray height and average ray width and it also concluded that ray proportion and dimensions appears to be fairly under genetic control. Environment has a greater influence in deciding the size of ray height. This is because of the fact that an environmental stress reduces rate of cambial growth, there by ray height may be reduced (Larson, 1994). Significant, locality wise variation at one percent level significance was observed with regard to ray height, ray width and ray frequency in the present study which might be due to the variability in growing conditions (edaphic factors) and the genetic makeup of the samples studied.

5.5 Biochemical properties

5.5.1 Extractive content

The quantity of total extractive content as an indicator of relative natural durability of teak has been established by several researchers (Simatupang et al., 1996; Yamamoto et al., 1998). The present study showed significant variation in total extractive content (%) with regard to growth rate and location of the sample. Slow grown samples showed 22 percent higher extractive content than fast grown samples. Similar observations were made by Bhat et al. (2004) in wet and dry locality teak.

Significant location-wise variation was also observed in the present study. The extractive content varied from 5.02 to 11.13 % between the sample localities. Wood extractive content was found to have considerable influence on heartwood colour of teak. The sample from Konni showed high amount of extractive content (11.13 %), followed by Betul (10.44 %) and was found to have more dark coloured heartwood (Table 14; Table 10). Similar values for extractive content were reported by Indira et al. (2010) for teak from central India and Konni. In an earlier study, Bhat et al. (2005) reported 12 percent extractive content in Nilambur teak, whereas in the present study, only 8 % extractive content was observed for the samples from Nilambur. The lower extractive content in the samples from

Vadavar and Sudan might be the reason behind their lighter coloured heartwood. The present study also observed a significant positive correlation between heartwood percentage and extractive content (Table 20). Teak wood from high rainfall areas were found to be paler in colour due to lower amount of extractives and were more susceptible to brown rot fungi (Bhat et al., 2005). Furthermore, Thulasidas and Bhat (2007) found positive correlation with individual extractive compounds rather than total extractive content responsible for decay resistance of timber in home garden teak. In the present study, relatively higher extractive content percent was observed for the samples from Konni, Betul, Trinidad, Myanmar, Malayattoor, Thailand, Nilambur and Cameroon, compared to the remaining localities.

5.6 Conclusions

The present study revealed some interesting findings on the variation in wood properties of teak with regard to rate of growth and locality. Fast grown teak had higher specific gravity, moisture content (air dry) and shrinkage compared to the slow grown whereas slow grown teak had higher vessel diameter, vessel area, ray height, ray width and extractive content percent. However, fast and slow grown teak do not differ in terms of coefficient of anisotropy (wood stability), heartwood percentage, heartwood colour, bark thickness as well as vessel and ray frequency. Thus from the results of the present study it can be concluded that, rate of growth has only a little effect on the wood quality of teak which is in agreement with the findings of many similar studies.

Variation in wood properties was found to be even higher when teak samples from different localities were compared (Table 21). Ring width varied significantly between the 14 localities. Teak from Africa showed higher ring width ($\geq$ 5 mm) and therefore considered as fast grown and was comparable or even faster (Ghana) than that of fast grown Nilambur teak. Significant variation in wood properties was encountered with Asian teak, especially the teak samples from India showed high variability with regard to growth rate/ring width. Maximum growth rate was showed by Vadavar teak (Tamil Nadu).

Asian teak showed significantly higher specific gravity than the samples from Africa. Among the sample locations, higher specific gravity was recorded for the samples from Vadavar (Tamil Nadu) (0.71) and Nilambur (0.68) and the lowest (0.55) for the sample from Ghana.

Tangential shrinkage observed for teak from Sudan and Trinidad was at par with that of teak from Nilambur, Konni and Malayattoor. Lowest coefficient of anisotropy was shown by Nilambur teak, while value for the same was comparable with the teak samples from Tanzania, Vadavar (Tamil Nadu) and Betul (Madhya Pradesh). Relatively higher value for coefficient of anisotropy was shown by African teak (Ghana, Cameroon, Benin and Sudan).

Wood colour as determined by Munsell notation, varied among the sample locations from yellow to yellowish brown or even darker brownish yellow and also brown to dark and strong brown. Darker heartwood colour was displayed by the African samples, Benin was an exception. Trinidad had lighter coloured wood. Greater variability in heartwood colour was displayed by the teak samples from native localities viz. India, Thailand, and Myanmar. Though teak from Vadavar (TN) showed greater homogeneity with teak from Nilambur with regard to many other properties, it displayed a distinct lighter coloured wood than that of Nilambur teak.

The sample from Myanmar possessed the highest vessel dimensions and sample from Konni had the largest ray height and ray width; both these were categorised as slow grown samples. Total extractive content of the samples of 14 different locations indicated significant variation between localities. Samples from Konni (11.13 %) and Betul (Madhya Pradesh) (10.44 %) possessed high amount of extractives and more darker heartwood.

The study revealed that wood quality parameters such as specific gravity (Vadavar (TN) and Nilambur), resistance to deformation (Vadavar (TN), Betul

(MP) and Nilambur), heartwood colour and total extractive content (Konni and Betul (MP)) were found to be higher for Indian teak irrespective of their growth rate. The above foregoing ones again reiterates the overall superiority of wood quality of Indian teak, be it Nilambur, Konni, Tamil Nadu or Betul, compared to teak from other regions of the world.

Table 21. Wood property profile of teak grown at different locations

Wood properties	Sample Location													
	Nilambur (Kerala)	Ranni (Kerala)	Konni (Kerala)	Malayattoor (Kerala)	Vadavar (TN)	Betul (MP)	Myanmar	Thailand	Tanzania	Cameroon	Ghana	Benin	Sudan	Trinidad
Lat/long	11.2769^{0}N 76.2258^{0}E	9.3667^{0}N 76.7667^{0}E	9.2410^{0}N 76.8784^{0}E	10.1833^{0}N 76.5000^{0}E	10.8167^{0}N 79.1833^{0}E	21.8333^{0}N 77.8333^{0}E	22.0000^{0}N 96.0000^{0}E	15.3500^{0}N 101.0333^{0}E	6.3070^{0}N 34.8540^{0}E	5.1167^{0}N 11.9167^{0}E	7.6833^{0}N 0.9833^{0}E	8.8333^{0}N 2.1833^{0}E	15.0000^{0}N 32.0000^{0}E	10.6667^{0}N 61.5167^{0}E
RW (mm)	4.8	5.1	3.1	3.3	8.4	2.8	2.6	4.4	4.6	4.8	5.7	4.7	3.6	3.9
SG (G)	0.92	0.77	0.80	0.86	1.17	0.74	0.86	0.87	0.92	0.80	0.64	0.80	0.91	0.92
SG (AD)	0.73	0.71	0.64	0.76	0.81	0.68	0.71	0.72	0.67	0.68	0.60	0.73	0.64	0.69
SG (OD)	0.68	0.70	0.58	0.67	0.71	0.59	0.63	0.66	0.60	0.62	0.55	0.70	0.60	0.60
RS (G-OD)	3.04	2.74	2.21	2.09	2.77	2.53	2.01	2.22	3.00	2.39	2.53	2.26	2.22	2.06
TS (G-OD)	4.60	5.29	4.66	4.19	4.95	4.28	5.44	4.73	4.99	4.89	5.14	5.41	4.57	4.28
CoA	1.55	2.20	2.27	2.22	1.89	1.89	2.79	2.16	1.74	2.42	2.37	2.70	2.13	2.23
MC (G)	64.26	72.54	42.78	60.59	63.80	80.39	58.88	52.18	61.40	53.75	67.63	53.42	41.02	61.52
MC (AD)	15.7	16.25	13.35	13.97	15.14	14.36	12.97	12.31	14.93	15.36	17.51	15.87	14.14	13.92
HW colour	Brown	Dark brown	Dark brown	Brownish yellow	Yellow	Brown	Yellowish brown	Yellowish brown	Strong brown	Brownish yellow	Strong brown	Brownish yellow	Yellowish brown	Yellowish brown
VD	206.02	212.08	282.75	222.82	223.33	237.75	342.92	143.67	221.67	205.50	230.42	265.68	223.25	258.67
VA	50746.6	49657.3	88583.4	57890	58794.3	61932.5	117653.6	28504	58536.2	44985.7	58226.7	81446.4	62112.3	73909.7
VF	4	7	6	9	9	6	3	6	8	6	7	6	7	7
RH	542.75	554.42	1065.23	669.67	717.17	680.75	665.17	668.92	606.25	645.58	680.27	703.33	645.50	649.08
RW	48.83	44.75	96.01	52.67	64.33	40.75	47.41	77.75	42.00	80.08	65.83	47.16	52.42	52.42
RF	4	9	5	8	8	7	5	5	9	7	7	4	7	8
EC (%)	8.05	6.21	11.13	9.22	7.47	10.44	9.64	8.81	7.13	7.82	6.89	6.61	5.02	10.19

Where: Lat/long- Latitude and longitude; RW – Ring width; SG (G) – Specific gravity (green basis); SG (AD) – Specific gravity (air dry basis); SG (OD) – Specific gravity (oven dry basis); RS (G-OD) – Radial shrinkage (green to oven dry); TS (G-OD) - Tangential shrinkage (green to oven dry); CoA – Coefficient of anisotropy; MC (G) – Moisture content (green basis); MC (AD) – Moisture content (air dry basis); HW colour – Heartwood colour; VD – Vessel diameter; VA – Vessel area; VF – Vessel frequency; RH – Ray height, RW – Ray width, RF – Ray frequency; EC (%) – Extractive content percent.

SUMMARY

SUMMARY

In a study titled "Effect of growth rate on wood quality of teak grown under differing site quality conditions", wood samples were collected from saw mills and major ports of imports of timber in South India and analysed for wood properties in Wood science laboratory, College of forestry, Kerala Agricultural University during 2011-2013.

The wood samples were classified in to fast grown and slow grown based on the mean ring width. Those samples having an average ring width $\geq$ 5 mm and those having an average ring width < 5 mm were categorised into fast grown and slow grown respectively. The fast grown category included the teak samples from Nilambur, Vadavar, Ranni, Benin, Tanzania, Cameroon and Ghana, while the samples from Konni, Malayattoor, Betul, Myanmar, Thailand, Sudan and Trinidad came under the slow grown category.

The major findings are summarised below:-

1. Specific gravity : Specific gravity in green, air dry and oven dry conditions were found to be significant with regard to sample growth rate and locations. The fast grown samples showed a 4.5 % higher specific gravity compared to the slow grown samples. Highest specific gravity was recorded for the samples from Vadavar (Tamil Nadu), Benin and Nilambur, while lowest value was found for Ghana. Teak samples from Asia possessed greater specific gravity than the samples from Africa.

   Among the samples from India, samples from Nilambur, Vadavar, Malayattoor and Ranni had the highest specific gravity values. Konni and Betul (Madhya Pradesh) had the lowest specific gravity.

   Correlation analysis showed weak correlations between specific gravity and different anatomical properties. Ray width was found to be slightly negatively correlated to air dry specific gravity. Among anatomical properties, vessel area and vessel diameter showed significant positive

correlation between each other, while both vessel area and vessel diameter was found to be having significant negative correlation with vessel frequency.

The correlation of physical properties like shrinkage and moisture content with specific gravity was found to be non-significant. Extractive content (%) was found to be negatively correlated with air dry specific gravity; whereas hue (red to yellowness) value of heartwood colour was found to have significant positive correlation with air dry and oven dry specific gravity.

2. Wood shrinkage: Wood shrinkage (radial and tangential) showed significant variation between the fast and slow grown samples. Variation in radial shrinkage between the sample locations was found to be non-significant, but for tangential shrinkage, difference with respect to sample locations was found to be significant.

The fast grown samples had 18 % greater radial shrinkage compared to slow grown samples. The faster grown samples had a values range of 2.25 % to 3.04 %, while the slow grown sample got a value range 2.01 % to 2.53 % for radial shrinkage (green to oven dry).

Tangential shrinkage (green to oven dry) showed significant variation between the fast and slow grown as well as between the sample locations. Tangential shrinkage (Green to air dry) was also found to be significantly different with regard to sample locations. The fast grown samples showed 8 % greater tangential shrinkage compared to the slow grown samples. Nilambur sample showed homogeneity with the slow grown samples in the case of tangential shrinkage (green to oven dry).

The coefficient of anisotropy (the ratio of tangential to radial shrinkage) was least for the Nilambur teak, followed by the samples from Tanzania, Vadavar (Tamil Nadu) and Betul (Madhya Pradesh), which indicates a low risk of deformation in wood during drying.

3. Moisture content: Variation in moisture content (green) was found to be significant only with regard to sample locations, whereas air dry moisture content had significant difference between fast and slow grown samples at 1 percent significance level. The sample from Betul (Madhya Pradesh) had the highest value, while Sudan had the lowest. Fast grown samples showed higher percentage of air dry moisture content compared to slow grown samples.

   Radial shrinkage at air dry to oven dry and green to oven dry conditions showed significant positive correlation with moisture content on air dry basis.

4. Heartwood percentage: Variation in heartwood percentage between fast and slow grown teak was found to be non-significant, but compared to the fast grown samples, 12 percent higher mean was shown by the slow grown samples.

   Heartwood percentage showed significant negative correlation with green to oven dry tangential shrinkage at 5 percent level, while extractive content (percent) showed a weak but negative correlation at 1 percent level of significance.

5. Heartwood colour: Heartwood colour determining components viz. hue (red to yellowness), value (lightness) and chroma (saturation) did not show any significant variation between the fast and slow grown samples.

   Wood colour as determined by Munsell notation, varied among the 14 sample locations from yellow to yellowish brown or even darker brownish yellow and also brown to dark and strong brown. Darker heartwood colour was displayed by the African samples, Benin was an exception. Trinidad had lighter coloured wood. Greater variability in heartwood colour was displayed by the native localities of teak viz. India, Thailand, and Myanmar.

6. Bark thickness: There was no significant difference between the samples of fast and slow grown categories with regard to bark thickness. Though the results were non-significant, the faster grown samples showed a higher mean for bark thickness than the slow grown samples.

7. Vessel diameter: Variation in vessel diameter and vessel area was found to be significant between the fast and slow grown samples; also both showed significant variation among the sample locations. Slow grown teak samples showed greater vessel diameter and area compared to fast grown samples. Largest vessel diameter and vessel area was found for the sample from Myanmar and the sample from Thailand had the lowest.

   Green to oven dry tangential shrinkage showed a weak but significant positive correlation with vessel diameter.

8. Vessel frequency: Significant location-wise variation was found with regard to vessel frequency ($p < 0.001$). The vessel frequency ranged from 3 to 9 and the lowest vessel frequency was observed for the sample from Myanmar and was comparable with that of Nilambur sample, while the highest vessel frequency was observed for the teak sample from Malayattoor.

9. Ray height: Both ray height and ray width showed significant variation with regard to the growth rate and sample location, while variation in ray frequency was found significant only with regard to sample locations. Slow grown samples had larger ray dimensions compared to fast grown samples. The sample from Konni possessed the largest ray height and ray width, whereas samples from Nilambur had the lowest ray height. The higher vessel frequency was found for the samples from Tanzania and Ranni.

Ray height was found to have significant positive correlation with value and chroma components of heartwood colour. Both the components viz. value and chroma, also showed significant positive correlation with hue, which is the third colour determining component.

10. <u>Extractive content</u>: Variation in extractive content (%) was found to be highly significant ($p < 0.001$) with respect to growth rate and location of the sample. Slow grown samples had 22 percent higher extractive content than fast grown samples. Among the sample localities, samples from Konni (11.13 %) and Betul (Madhya Pradesh) (10.44 %) possessed high amount of extractives, whereas the sample from Sudan had the lowest.

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APPENDICES

APPENDICES

Appendix I. ANOVA for comparing specific gravity (green)

Source	df	Sum of Squares	Mean Square	F	P-value
Between Growing condition	1	0.001	0.001	0.61^{ns}	0.439
Locations within Growing condition	12	0.860	0.068	31.81**	< 0.001
Error	43	0.097	0.002		
Total	56	0.966			

*** significant at 0.01 level; ns non significant at 0.05 level*

Appendix II. ANOVA for comparing specific gravity (air dry)

Source	df	Sum of Squares	Mean Square	F	P-value
Between Growing condition	1	0.002	0.002	3.15^{ns}	0.083
Locations within Growing condition	12	0.184	0.015	27.56**	< 0.001
Error	43	0.024	0.001		
Total	56	0.213			

*** significant at 0.01 level; ns non significant at 0.05 level*

Appendix III. ANOVA for comparing specific gravity (oven dry)

Source	df	Sum of Squares	Mean Square	F	P-value
Between Growing condition	1	0.011	0.011	22.85**	< 0.001
Locations within Growing condition	12	0.111	0.009	19.96**	< 0.001
Error	43	0.020	0.0005		
Total	56	0.146			

*** significant at 0.01 level*

Appendix IV. ANOVA for comparing vessel diameter

Source	df	Sum of Squares	Mean Square	F	P-value
Between Growing condition	1	8816.30	8816.30	11.28**	0.001
Locations within Growing condition	12	123670.84	10305.90	13.187**	< 0.001
Error	56	43763.50	781.49		
Total	69	176250.64			

*** significant at 0.01 level*

Appendix V. ANOVA for comparing vessel Area (log transformed)

Source	df	Sum of Squares	Mean Square	F	P-value
Between Growing condition	1	0.34	0.34	5.92*	0.018
Locations within Growing condition	12	6.90	0.57	10.090**	< 0.001
Error	56	3.19	0.06		
Total	69	10.42			

*** significant at 0.01 level; * significant at 0.05 level*

Appendix VI. ANOVA for comparing vessel frequency

Source	df	Sum of Squares	Mean Square	F	P-value
Between Growing condition	1	0.08	0.08	0.11^{ns}	0.075
Locations within Growing condition	12	141.51	11.79	16.395**	< 0.001
Error	56	40.28	0.72		
Total	69	181.86			

*** significant at 0.01 level; ns non significant at 0.05 level*

AppendixVII. ANOVA for comparing ray height

Source	df	Sum of Squares	Mean Square	F	P-value
Between Growing condition	1	126245.47	126245.47	28.18**	< 0.001
Locations within Growing condition	12	844294.52	70357.88	15.705**	< 0.001
Error	56	250878.53	4479.97		
Total	69	1221418.53			

*** significant at 0.01 level;*

Appendix VIII. ANOVA for comparing ray width

Source	df	Sum of Squares	Mean Square	F	P-value
Between Growing condition	1	249.37	249.37	6.09*	0.017
Locations within Growing condition	12	17536.50	1461.37	35.694**	< 0.001
Error	56	2292.71	40.94		
Total	69	20078.58			

*** significant at 0.01 level; * significant at 0.05 level*

Appendix IX. ANOVA for comparing ray Frequency

Source	df	Sum of Squares	Mean Square	F	P-value
Between Growing condition	1	2.27	2.27	2.87^{ns}	0.096
Locations within Growing condition	12	177.91	14.83	18.745	< 0.001
Error	56	44.29	0.79		
Total	69	224.48			

*** significant at 0.01 level; ns non significant at 0.05 level*

Appendix X. ANOVA for comparing radial shrinkage (green to air dry)

Source	df	Sum of Squares	Mean Square	F	P-value
Between Growing condition	1	0.339	0.339	6.48*	0.015
Locations within Growing condition	12	0.749	0.062	1.195	0.323
Error	41	2.142	0.052		
Total	54	3.211			

** significant at 0.05 level; ns non significant at 0.05 level*

Appendix XI. ANOVA for comparing radial shrinkage (air dry to oven dry)

Source	df	Sum of Squares	Mean Square	F	P-value
Between Growing condition	1	1.386	1.386	9.55**	0.004
Locations within Growing condition	12	2.823	0.235	1.622^{ns}	0.114
Error	41	5.948	0.145		
Total	54	10.268			

*** significant at 0.01 level; ns non significant at 0.05 level*

Appendix XII. ANOVA for comparing radial shrinkage (green to oven dry)

Source	df	Sum of Squares	Mean Square	F	P-value
Between Growing condition	1	3.200	3.200	25.32**	< 0.001
Locations within Growing condition	12	2.780	0.232	1.833^{ns}	0.069
Error	41	5.182	0.126		
Total	54	11.236			

*** significant at 0.01 level; ns non significant at 0.05 level*

Appendix XIII. ANOVA for comparing tangential shrinkage (green to air dry)

Source	df	Sum of Squares	Mean Square	F	P-value
Between Growing condition	1	0.492	0.492	2.47^{ns}	0.124
Locations within Growing condition	12	5.120	0.427	2.141*	0.035
Error	41	8.171	0.199		
Total	54	13.791			

** significant at 0.05 level; ns non significant at 0.05 level*

Appendix XIV. ANOVA for comparing tangential shrinkage (air dry to oven dry)

Source	df	Sum of Squares	Mean Square	F	P-value
Between Growing condition	1	0.780	0.780	2.35^{ns}	0.133
Locations within Growing condition	12	5.657	0.471	1.424^{ns}	0.195
Error	41	13.578	0.331		
Total	54	20.035			

ns non significant at 0.05 level

Appendix XV. ANOVA for comparing tangential shrinkage (green to oven dry)

Source	df	Sum of Squares	Mean Square	F	P-value
Between Growing condition	1	2.707	2.707	17.58**	<0.001
Locations within Growing condition	12	6.122	0.510	3.312**	0.002
Error	41	6.315	0.154		
Total	54	15.199			

*** significant at 0.01 level*

Appendix XVI. ANOVA for comparing moisture content (green)

Source	df	Sum of Squares	Mean Square	F	P-value
Between Growing condition	1	446.73	446.73	2.73^{ns}	0.106
Locations within Growing condition	12	5229.35	435.78	2.66**	0.009
Error	43	7040.29	163.73		
Total	56	12657.74			

*** significant at 0.01 level; ns non significant at 0.05 level*

Appendix XVII. ANOVA for comparing moisture content (air dry)

Source	df	Sum of Squares	Mean Square	F	P-value
Between Growing condition	1	71.16	71.16	21.11**	<0.001
Locations within Growing condition	12	31.43	2.62	0.78^{ns}	0.670
Error	43	144.96	3.37		
Total	56	246.02			

*** significant at 0.01 level; * significant at 0.05 level*

Appendix XVIII. ANOVA for comparing extractive content (%)

Source	df	Sum of Squares	Mean Square	F	P-value
Between Growing condition	1	43.70	43.70	44.67**	<0.001
Locations within Growing condition	12	80.03	6.67	6.82**	<0.001
Error	28	27.39	0.98		
Total	41	151.12			

*** significant at 0.01 level;*

Appendix XIX. ANOVA for comparing coefficient of anisotropy

Source	Sum of Squares	df	Mean Square	F	P-value
Between Growing conditions	.552	1	.552	$.836^{ns}$	.362
Within Groups	110.325	167	.661		
Total	110.877	168			

ns non significant at 0.05 level

Appendix XX. ANOVA for comparing coefficient of anisotropy

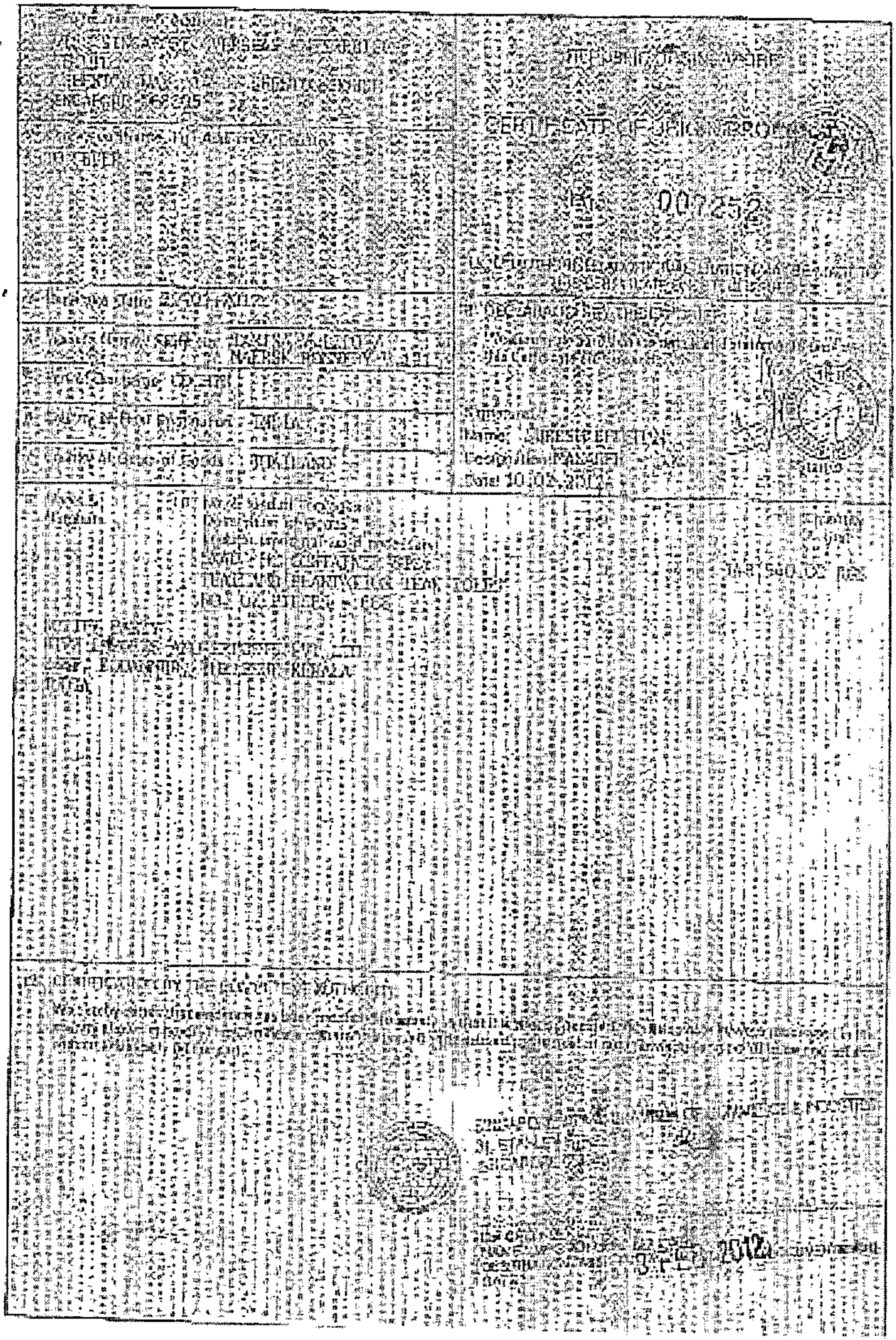
Source	df	Sum of Squares	Mean Square	F	P-value
Between Locations	13	18.163	1.397	2.326*	.008
Within Groups	154	92.511	.601		
Total	167	110.674			

** significant at 0.05 level*

Appendix XXI. Comparison of other physical properties between fast and slow grown samples

Parameters	Growth Rate	Mean	Std. Deviation	
Heartwood (%)	Fast	69.294	16.182	1.572
	Slow	79.702	6.429	
Hue	Fast	8.571	1.336	1.044
	Slow	9.286	1.220	
Value	Fast	5.286	0.756	0.795
	Slow	5.000	0.577	
Chroma	Fast	5.714	1.380	0.354
	Slow	6.000	1.633	
Bark Thickness (mm)	Fast	5.910	1.630	2.195
	Slow	3.965	1.561	

XXII. Certificate of origin of samples collected from Thailand



XXIII. Certificate of origin of samples collected from Myanmar

GOVERNMENT OF THE UNION OF MYANMAR
MINISTRY OF FORESTRY
MYANMA TIMBER ENTERPRISE

CERTIFICATE OF ORIGIN

No 026736

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

M/S SURABI WOODS NEAR RAILWAYS STATION ANGAMALY, P.O ERNAKULAM.
KERALA, INDIA.

BY SEA ROUTE TO YANGON/COCHIN.

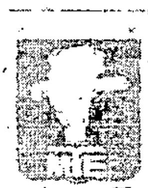
TEAK ROUND LOGS.

101 PCS	63.036 H.TONS	EB 405/GT/ 2009-2010	DT. 24-7-2009

MEASURING HOPPUS TONS SIXTY THREE POINT ZERO THREE SIX ONLY.

YAAD E MUSTAFA.

YANGON COCHIN



(Khine Khine Soe)
Assistant Manager
Export Bills Section
Myanma Timber Enterprise

18-8-2009.

XXIV. Certificate of origin of samples collected from Ghana

1 Exporter (Name & Address)

ROBUST INTERNATIONAL PTE LTD
7600A BEACH ROAD 07-310/311 THE PLAZA
SINGAPORE-199591

REPUBLIC OF SINGAPORE

CERTIFICATE OF ORIGIN/PROCESSING

No. 022845

NO UNAUTHORISED ADDITION/ALTERATION MAY BE MADE TO THIS CERTIFICATE ONCE IT IS ISSUED

2 Consignee (Name, Full Address & Country)

GURUDEV CORPORATION
S.NO.94/1A, PLOT NO.7
NANDED ROAD, LATUR 413512
MAHARASHTRA INDIA.

3 Departure Date 30.04.2012

4 Vessel's Name / Flight No. M.V.CMA CGM AFRICA ONE V.NO.WVS16606

5 Port of Discharge MANGALORE

6 Country of Final Destination INDIA

7 Country of Origin of Goods TEMA PORT GHANA

8 DECLARATION BY THE EXPORTER

I hereby declare that the details and statements provided in this Certificate are true and correct.

Signature: [signature]

Name: ANURADHA

Designation: MANAGER

Date: 07.05.2012

Stamp: ROBUST INTERNATIONAL PTE LTD

9 Marks & Numbers | 10 No. & Kind of Packages Description of Goods (include brand names if necessary) | 11 Quantity & Unit

- GHANA ORIGIN TEAK ROUND LOGS

TOTAL PCS /HTONS/CBM
36 PCS/21.4140 CBM

LC NO:31620NI00007812 DTD 04.04.2012

UNION BANK OF INDIA
Foreign Exchange Dept.
PAD No. 81 94 12
Byculla Branch, For Ex.

12 CERTIFICATION BY THE COMPETENT AUTHORITY

We hereby certify that evidence has been produced to satisfy us that the goods specified above originate in/were processed in the country shown in box 7. This Certificate is therefore issued and certified to the best of our knowledge and belief to be correct and without any liability on our part.

SINGAPORE INDIAN CHAMBER OF COMMERCE & INDUSTRY
31, STANLEY STREET
SINGAPORE 068740

For CEO / SECRETARY
NAME : MRS K R GUNASUNDARI
DESIGNATION : ASSISTANT MANAGER (TRADE DOCUMENTATION)
DATE : 07 MAY 2012

XXV. Certificate of origin of samples collected from Benin

... DU BENIN

MINISTERE DE L'INDUSTRIE ET DU COMMERCE

DIRECTION GENERALE DU COMMERCE EXTERIEUR

DIRECTION DE LA PROMOTION DU COMMERCE EXTÉRIEUR

SERVICE DES ECHANGES COMMERCIAUX ET DE LA REGLEMENTATION

CERTIFICAT D'ORIG

POUR LES PRODUITS D'EXPORT

N° 0234/12 MIC/DGCE/DP

Nature, Nombre Marque et Numéro des colis

01 X 40' CONTAINER SAID TO CONTAIN 119 PIECES OF TEAK LOGS

Nous soussignés DIRECTEUR DE LA PROMOTION DU COMM

Directeur de la Promotion du Commerce Exterieur

Certifions :

1 Que M (1) FRED AND FRED P/C VKR IMPORTS & EXPOR

demeurant à COTONOU - BENIN

Nous a présenté pour être embarqué sur le navire (2) MSC I V. 4B120R à destination de (3) TUTICORIN

la quantité de (4) 119 PIECES OF TEAK LOGS

dont les marques et numéros sont indiqués en marge contenant les marcha

détaillées ci-après (5) 01 X 40' CONTAINER SAID TO CONTAIN 119 PIECES OF TEAK LOGS

TIMBRE FISCAL 500 FRANCS

du poids (6) Brut VINGT DEUX MILLE KILOS (22000.000 KGS)
Net VINGT DEUX MILLE KILOS (22000.000 KGS)

2° Que ces marchandises sont originaires de la République du Bé

A COTONOU, le 28 / 02 / 201

Référence du Contrat :

Mode de Paiement :

Nous soussignés, Agent des Douanes du Bureau de COTONOU-POR

certifions que les marchandises ci-dessus mentionnées, ont fait l'objet de l

déclaration d'exportation n° ... du ...

à destination de TUTICORIN, navire MSC INDIA V. 4B120

A COTONOU le 28 / ...

Le Chef de Bureau, L'Insp...

DOUANES BENIN VISITE COTONOU PORT

Vu à l'embarquement sur le navire

MSC INDIA V. 4B120R

A COTONOU, le 28 / 02 / 2012

Les Agents Brevetés

(1) Nom de l'Exportateur
(2) Pavillon et nom du navire
(3) Port de destination
(4) Nombre et espèce des colis, sacs, caisses, fûts etc
(5) Espèce de la marchandise
(6) Poids (en toutes lettres)

XXVI. Certificate of origin of samples collected from Cameroon

M... DES EAUX, FORETS, CHASSE & PECHE ... ARGE DE L'ENVIRONNEMENT

DIRECTION DE CABINET

DIRECTION GENERALE DES SERVICES REGIONAUX

DIRECTION REGIONALE N°6

INSPECTION FORESTIERE PREFECTORALE DE LA BASSE - KOTTO

N° 069 /MEFCPE/DIR.CAB/DGSR/DR6/IFPBK.

REPUBLIQUE CENTRAFRICAINE

Unité-Dignité-Travail

PROGRAMME DE SECURISATION DES RECETTES FORESTIERES

Check Point Routier de Nyalla

CHEF D'EQUIPE M. KAMENI

N° VEHICULE

DESTINATION Port DLA

DATE 27 FEV 2012

PROVENANCE RCA

OBSERVATION

SIGNATURE

CERTIFICAT D'ORIGINE

Préfecture de : LA BASSE- KOTTO

Sous Préfecture de : MOBAYE

Nous soussigné : DOUI Celestin LT Col DES EAUX et Forêts

Certifions que les produits forestiers suivants :

DESIGNATION	QUANTITE	POIDS	VOLUME (m3)
Grumes (billes)	86 billes	24,554 T	~~20.462 m³~~ 20.743 m³

Lieu de fabrication/Récolte : MOBAYE

Nom de l'acheteur : KINANI CO.

Destination : DOUALA

Nom du destinataire : KINANI CO

Moyen de transport : VEHICULE DR 829 BG

INDIAN BANK ERNAKULAM FIBG

Fait à Alindao, le 26.01.2012

L'INSPECTEUR PREFECTORAL DE LA BASSE - KOTTO

INSPECTION FORESTIERE DE LA BASSE-KOTTO • MEFCP • L'INSPECTEUR

Lt Col. DOUI Célestin

XXVII. Certificate of origin of samples collected from Sudan

1 Exporter (Name & Address)

WOOD CRAFT INTERNATIONAL PTE LTD.
180 CECIL STREET,
#15-01, BANGKOK BANK BUILDING
SINGAPORE - 069546

REPUBLIC OF SINGAPORE

CERTIFICATE OF ORIGIN/~~PROCESSING~~

No 032857

NO UNAUTHORISED ADDITION/ALTERATION MAY BE MADE TO THIS CERTIFICATE ONCE IT IS ISSUED

2 Consignee (Name, Full Address & Country)

TO ORDER

3 Departure Date 12.05.12

4 Vessel's Name / Flight No. M.V.CMA CGM LA TOUR

5 Port of Discharge MUNDRA

6 Country of Final Destination INDIA

7 Country of Origin of Goods SUDAN

8 DECLARATION BY THE EXPORTER

We hereby declare that the details and statements provided in this Certificate are true and correct.

Signature: [signature]
Name: RAJESH PRAVINKUMAR CHEVLI
Designation: DOCUMENTATION OFFICER
Date: 26.06.12

Stamp

9 Marks & Numbers	10 No. & Kind of Packages Description of Goods (include brand names if necessary)		11 Quantity & Unit
		4 X 20' CONTAINER	
	681 PCS	TEAK LOGS	58.088 CBM

WE HEREBY CERTIFY THAT THE ABOVE GOODS ARE OF SUDAN ORIGIN

12 CERTIFICATION BY THE COMPETENT AUTHORITY

We hereby certify that evidence has been produced to satisfy us that the goods specified above originate in/were processed in the country shown in box 7. This Certificate is therefore issued and certified to the best of our knowledge and belief to be correct and without any liability on our part.

SINGAPORE [illegible] CHAMBER OF COMMERCE & INDUSTRY
[illegible], SICCI BUILDING
SINGAPORE [illegible]

[illegible] SUNDARI
NAME: [illegible]
DESIGNATION: ASSISTANT MANAGER (TRADE DOCUMENTATION)
DATE:

2 6 JUN 2012

XXVIII. Certificate of origin of samples collected from Tanzania

UNITED REPUBLIC OF TANZANIA — CERTIFICATE OF ORI[GIN]

1 Exporter (Name and Address)

M/S ARIDHI EXPORTS LIMITED
P.O. BOX 48
TANGA
TANZANIA

2 Reference

No. A — № 0000058390

3 Consignee (Name and address)

M/S TO ORDER

4 Particulars of transport (if required by importer)

BY SEA

5 Marks & Number, Number of packages, Description of goods

1,682 PCS OF TECTONA GRANDIS

2,361 PCS OF AFRICAN SALWOOD

6. Gross weight

KG

10,000

7 In cu[bic meters]

8 Other information

F.O.B VALUE:

[illegible] SEAL OF THE CHAMBER

9. It is hereby certified that the above mentioned goods originate in [illegible]

TANZANIA CHAMBER OF COMMERCE, INDUSTRY & AGRICULTURE

Place: 10/04/2012

Date: CHARLES L. HOZZA - EXT. O[FFICER]

Authorized signature

XXIX. Certificate of origin of samples collected from Trinidad and Tobago

SCHEDULE
CARIBBEAN COMMON MARKET
DECLARATION AND CERTIFICATE

Page: 1

[illegible] (Name, full address, country) [illegible] GUISEPPI [illegible] BRASSO TAMANA RD BRASSO	Exporter's Ref. No. 961506554 CARIBBEAN COMMON MARKET COMBINED DECLARATION BY EXPORTER AND CERTIFICATE OF ORIGIN
Consignee (Name, full address, country) TO ORDER	Country of issue TRINIDAD AND TOBAGO (Country) See note overleaf
Transport information (vessel / aircraft, place of loading, etc.) Port of Spain	Country of Origin: Trinidad and Tobago [illegible] of destination: India For Official Use

Item Number	Marks and Number of Packages	Number and Kind of packages, description of goods.	Origin criterion (see notes overleaf)	Gross Weight or other quantity	Number and date of invoices
1	AS ADDRESSED	9 cn. 9X20 TRINIDAD ROUGH SQUARED TEAK LOG GATU 0144455 158PCS 19.969M3 SCIU 4539116 154PCS 18.925M3 SCMU 1428454 193PCS 20.289M3 CRLU 3144421 160PCS 17.595M3 SCMU 1798575 125PCS 15.161M3 BVRU 1458150 205PCS 19.196M3 CMAU 1954159 147PCS 17.405M3 SCMU 2188049 174PCS 19.422 CMAU 0948101 193PCS 17.543M3 [illegible]	[illegible]	[illegible]	961506554 [illegible]

CERTIFICATION	DECLARATION BY THE EXPORTER
It is hereby certified, on the basis of control carried out, that the declaration by the exporter is correct. [signature] 20/02/12 The Energy Chamber of Trinidad & Tobago Place and date, signature and stamp of certifying authority	I, the undersigned, hereby declare that the above details and statements are correct, that all the goods [illegible] were produced [illegible] country, and that they [illegible] the determination of origin set out in Articles 14 and 16 of and schedule I to the annex to the Treaty establishing the Caribbean Community. PORT OF SPAIN, TRINIDAD [illegible] Place and date, signature of [illegible] authorised signatory

XXX. Certificate of origin of samples collected from Madhya Pradesh

(NILAMBUR NORTH DIVISION)

Vazhikkadavu .... ഫോറസ്റ്റ് ഓഫീസർ / റെയ്ഞ്ച് / സ്റ്റേഷൻ / ചെക്ക്

Nilambur North .... വനം ഡിവിഷൻ

പാസ് നമ്പർ ....

തടിയോ മറ്റ് വനോൽപ്പന്നമോ കൊണ്ടുപോകുന്നതിനുള്ള പാസ്

1. പാസ് നൽകപ്പെടുന്ന വ്യക്തികളുടെ പേരും വസതിയും : Sabari Timbers, T. Kongadam, Mulappuram.
2. തടിയുടെയോ മറ്റ് ഉൽപ്പന്നത്തിന്റെയോ വിവരണവും അളവും : Teak wood, Round logs 48 Nos, 15.474 M3
3. അടയാളങ്ങൾ : Nil
4. എവിടെനിന്നു ലഭിച്ചു : Office of the Betul Timber Depot
5. എത്തിച്ചേരേണ്ട സ്ഥലം : Production Division Betul (M.P.)
6. മാർഗ്ഗം (മാർഗ്ഗമദ്ധ്യേയുള്ള ചെക്ക് സ്റ്റേഷൻ / സ്റ്റേഷനുകളുടെ പേര് എഴുതുക) : Via Vedayukam
7. അനുവദിച്ചിട്ടുള്ള സമയം : Two days
8. ... ഉൽപ്പന്നം കയറ്റുമതി ചെയ്യുന്നതിന് ആധാരമായ അസ്സൽ പാസിന്റെ നമ്പരും തീയതിയും : KNFD Form 29 Rule 14(4) dtd. 14/2/12, Form III 0774214

Lorry No: KL 10 AG 8685

Driver Abdulla

D/L No. 1257/01/13

സ്ഥലം : Anandapuram

തീയതി : 15/2/12

പാസ് നൽകുന്ന ഉദ്യോഗസ്ഥന്റെ ഒപ്പ്

പേര് : Jayachandran P.S

ഉദ്യോഗപ്പേര് : Forest guard

CHECKED

GPC. 19/105/2002. 5000-10...

XXXI. Certificate of origin of samples collected from Ranni

KERALA FOREST DEPARTMENT

FORM 1

[See rule 3 a (i)]

Form of Declaration for transporting timber of specified trees from outside 'notified areas' under Section 6

1. *Name and address of the applicant* : [illegible]
2. *Sy. No and extent of the field of fields on which the tree or the trees proposed to be cut uprooted or burnt stand* : 81/20
3. *Name of the Village/ Taluk/ Block and District where the land on which the trees stand/lie* : [illegible]
4. *Proof of ownership of the trees* : [illegible]
5. *List showing the species of tree or trees proposed to be cut or list of logs to be transported as the case may be etc. with GBH of the tree (14 m from ground level) serially numbered* : 89. [illegible]
6. *Purpose in which the tree/trees are proposed to be cut* : [illegible]
7. *Details of regeneration proposed* : [illegible]
8. *Place to which to be transported* : [illegible]

Place: [illegible]

Date: 15-11-10

Signature of the Applicant

DECLARATION

I hereby declare that the information furnished above is true to the best of my knowledge and belief. I undertake to comply with the conditions subject to which the permission may be granted by the autho officer.

Brok Cs. 44/10 dt 20-4-10.

Signature of the applicant

For Office Use only

1. *Date of receipt of the application by the authorised officer* 16-11-10
2. Orders of the authorised officer No objection is seen for transporting Teak Logs - 49 Nos, (Rs enclosed) to Chittarkadavu. Validity upto 25-11-1 The logs shall be got certified

Place: Ranni

Date: 20-11-10.

No.

Date

Authorised Officer

FOREST RANGE OFFICER

FOREST RANGE OFFICE RANNI

Note: (i) Application shall be presented in duplicate and one more copy shall be retained by the applicant

(ii) One copy with the order of the Authorised Officer shall be returned to the applicant.

XXXII. Certificate of origin of samples collected from Konni

Kerala Forest Department

Punalur Sales/Forest Division

78

FORM III
[See Rule 8(1)]
ORIGINAL

Pass No. 228/08

PASS FOR THE TRANSPORT OF TIMBER OR OTHER FOREST PRODUCE FROM GOVERNMENT FORESTS OR DEPOTS OR ELSEWHERE

1. Name and residence of person to whom pass is granted: Sadiq Ali, Tropical Supplies, Perumbavoor
2. Description of produce: Teak logs
3. Quantity: 38 × 9.970 m³ (Teak list attached)
4. Fees paid: Value 483052/- VAT 54759/- Cess 5481/- [illegible]
5. Marks: Dept. stock nos.
6. Whence obtained: Govt. Timber depot Konni
7. Destination: Perumbavoor [illegible]
8. Route (Specify the name of the Watch Station/Checking Station on the route): By Road
9. Time allowed: Till 23. [illegible]
10. Remarks: [illegible] to be got checked at [illegible] of watch stations.

Station : Konni

Date : 18-12-08

Signature of person granting the pass

Name DEPOT OFFICER KONNI

Designation

Office seal

[illegible]

N.B.—Enter No., species and measurement of each log or description of produce covered by the Pass, on the back.

GPC. [illegible] © Govt. of Kerala.

GOVERNMENT TIMBER DEPOT KONNI

Effect of growth rate on wood quality of teak (*Tectona grandis* Linn.f.) grown under differing site quality conditions.

By

ANISH, M.C.

ABSTRACT OF THE THESIS

Submitted in partial fulfillment of

the requirement for the degree of

Master of Science in Forestry

Faculty of Forestry

Kerala Agricultural University

DEPARTMENT OF WOOD SCIENCE

COLLEGE OF FORESTRY

KERALA AGRICULTURAL UNIVERSITY

VELLANIKKARA, THRISSUR -680 656

KERALA, INDIA

2013

ABSTRACT

The present study was carried out to analyse the effect of rate of growth on the wood quality of teak from samples collected from trees which were grown within the country as well as from outside. The work involved collection of samples from saw mills and major timber importing ports in South India (Mangalore, Tuticorin etc.) and wood property analysis that was carried out in the wood science laboratory, Department of Wood Science, College of forestry, Kerala Agricultural University, Vellanikkara. Teak samples (basal discs) from 14 different locations viz. Nilambur, Malayattoor, Konni, Ranni, Vadavar (TN) and Betul (MP) within India and Myanmar, Thailand, Ghana, Benin, Cameroon, Sudan, Tanzania and Trinidad outside India were included in the study.

To study the effect of growth rate on wood quality, the collected samples were classified as fast grown and slow grown based on their average ring width. Those samples having an average ring width ≥ 5 mm and those having an average ring width < 5 mm were categorised into fast grown and slow grown respectively. The analysis on variation in wood physical, anatomical and biochemical properties between the two categories revealed that, fast grown samples were characterized with higher specific gravity, moisture content (air dry) and shrinkage compared to the slow grown, but properties like vessel diameter, vessel area, ray height, ray width and extractive content (%) was found to be significantly higher for slow grown samples. However, fast and slow grown teak showed uniformity with regard to other properties such as coefficient of anisotropy (wood stability), heartwood content (%), heartwood colour and bark thickness.

Investigation on the wood properties between the samples from 14 different locations revealed higher degrees of variation. Ring width analysis showed that, samples from Africa (except Sudan) had higher growth rate and was comparable with that of fast grown Nilambur teak; Asian teak (especially the teak samples from India) showed high variability with regard to growth rate/ring

width. Maximum growth rate was showed by Vadavar teak (Tamil Nadu). The sample from Asia also showed superiority over the samples from Africa in the properties viz. specific gravity, wood stability, heartwood colour and extractive content (%). Among the samples from Asia, Myanmar possessed the highest vessel dimensions and the sample from Konni had the largest ray height and ray width. Samples from Konni (11.13 %) and Betul (Madhya Pradesh) (10.44 %) possessed higher amount of extractives and more darker heartwood. Wood quality parameters like specific gravity (Vadavar (TN) and Nilambur), resistance to deformation (Nilambur , Vadavar (TN) and Betul (MP)), heartwood colour and total extractive content (Konni and Betul (MP)) were found to be higher for Indian teak. Based on the present study, it can be concluded that, rate of growth has only a little effect on the wood quality of teak, whereas, location-wise, Indian teak irrespective of their growth rate, was found to be superior over rest of the samples with regard to wood physical, anatomical and biochemical properties.