WOOD QUALITY EVALUATION OF TREE SPECIES RAISED IN RESEARCH TRIALS OF THE KERALA FOREST DEPARTMENT AT VARIOUS LOCALITIES

By

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2010-17-107

THESIS

Submitted in partial fulfillment of the requirement for the degree of

MASTER OF SCIENCE IN FORESTRY

Faculty of Agriculture

Kerala Agricultural University

DEPARTMENT OF WOOD SCIENCE
COLLEGE OF FORESTRY
KERALA AGRICULTURAL UNIVERSITY
VELLANIKKARA, THRISSUR,
KERALA, INDIA
2012

DECLARATION

I hereby declare that this thesis entitled **"Wood quality evaluation of tree species raised in research trials of the Kerala Forest Department at various localities"** 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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ACKNOWLEDGMENT

With immense pleasure, I take this opportunity to express my deep sense of gratitude and indebtedness to Dr. E.V. Anoop, Associate Professor and Head, Dept. of Wood Science and Chairman of my advisory committee for his meticulous help, affectionate advice, valuable guidance, constructive suggestions, unfailing patience, friendly approach and timely help at various stages of my study programme.

I would like to express my extreme indebtedness and obligation to Dr. T.K. Kunhamu, Associate Professor and Head, officer in charge, AICRP on Agroforestry, Dept. of Silviculture and Agroforestry and member of my advisory committee for his timely support and critical scrutiny of the manuscript which has helped a lot for the preparation of my thesis.

Words are insufficient to express my thanks to Dr. P.O. Nameer, Associate Professor and Head, Dept. of Wildlife Sciences and member of my advisory committee for his ever willing help, valuable guidance and critical suggestions throughout the study.

I express my heartfelt gratitude to Dr. V. Jamaludeen, Assistant Professor, Dept. of Silviculture and Agroforestry and member of my advisory committee for his wholehearted co-operation and immense help extended throughout the study.

I would like to extend my thanks to Dr. K. Sudakara, Associate Dean, College of Forestry and Dr. B. Mohankumar, ADG, ICAR, Agronomy and Agroforestry for their keen interest and valuable suggestions provided during the course of my study.

I sincerely thank Dr. K. Vidyasagaran, Associate Professor and Head, Dept. of Forest Management and Utilization for his valuable suggestions. I am also grateful *to Mr. S. Gopakumar, Assistant Professor, Dept. of Forest Management and Utilization for his valuable advice extended to me during the study.*

I express my sincere gratitude to Dr. K.C. Chacko, KFRI and Dr. Jinu, Assistant Professor, AICRP on Agroforestry for their support during my study period.

I wish to express my gratitude to Dr. Sunandha for their guidance throughout the statistical analysis and interpretation of the data.

I acknowledge the financial support of the ITTO (International Tropical Timber Organisation) for undertaking the above work. I also acknowledge the support of the Kerala Forest Department for providing the study material for the above project.

Words cannot really express the true friendship that I relished with Mr. Aneesh, K.S. and Ms. Sukanya, S. for their whole hearted help and valuable suggestions which gave me enough strength to get through all mind-numbering circumstances.

I express my sincere gratitude to Shri. Shaji, Owner and other staff at TRC Saw Mill, Ancheri, Thrissur for their support during the conversion process.

The help rendered by Mrs. Prema, Mrs. Khadeeja, Mrs. Mini, Mrs. Reshmi, Ms. Sajitha, Mrs. Soumya, Mr. Rineesh and Mr. Aadersh are also remembered with gratitude.

My special thanks to Mrs. Jyothi for her patience in helping me in computer lab.

The love, support, care and encouragement of my dear friends Dhanya and Delphy gave me enough mental strength to get through all tedious circumstances. Words can't express my gratitude towards my friends; Shine, Shiran, Sreejith, and Sneha for their heartfelt help and support rendered throughout the study. The support and timely help provided my junior friends, Akhilesh, Iqbal, Niyas, Sachin, Devika Sanghamithra, Harikrishnan, Akhil R. Nath, Asif, Sreekumar, Vishnu, Shyamili, Hari and Abha are gratefully acknowledged.

The precious friendship, constant support and helping hands provided from my juniors Ms. Anju S. Vijayan and Ms. Anju V.R. Ms. Vinu Jacob, Ms. Soorya Soman, Ms. Mereena, Ms. Parvati Venugopal, Mr. Vishnu, Mr. Aneesh and Ms. Jyothy are remembered with gratitude.

I extend my unreserved thanks to Mr. Ratheesh, Mr. Sameer, Mr. Krishnadas, Mr. Rakesh, Mr. Shebin, Mr. Sooraj, Mr. Javed, Mr. Mumtaz, Ms. Priya for their timely help and support during thesis writing.

A word of apology to those have not been mentioned in person and a note of thanks to one and all who worked for the successful compilation of this endeavor.

At this juncture, I express my deep love to my parents, sister, brother and all family members without whose moral support, blessings and affection this would not have been a success.

Above all I bow my head before the God, ALMIGHTY whose blessings enabled me to undertake this venture successfully.

Sindhumathi, C.R.

Dedicated to My Family, friends

&

Dept. of Wood science

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INTRODUCTION

Wood is a remarkable material with the variability and flexibility that makes it useful for many kinds of products. The steady increase in the demand for wood, resulting from a concomitant increase in its applications implies that pressure on forest is constantly increasing. The need to cut down trees for wood is in direct conflict with the need to preserve forests for the conservation of biodiversity and as sinks for carbon dioxide. It is therefore essential that forest is managed sustainably, if demand is to continued be met without detriment to our environment (Barnett and Jeronimidis, 2003). This can be achieved by developing new forests and replacing trees that are harvested, while at the same time, trees are grown to produce wood of good quality.

Plantations of fast growing species are being raised on a massive scale all over the country under different plantation programmes for meeting the increasing demand for fuel, fodder and timber. As acute shortage of timber is being felt by wood based industries, plantations of various species are being harvested at an early stage before maturity (Shukla et al., 1990.)

Wood quality forms the ultimate basis which decides its utility for various purposes and it is determined largely by the cellular, anatomical and mechanical properties of the wood. Hence, evaluation of timber quality is a prerequisite for the proper utilization of wood. Wood characteristics often vary as greatly within the range of a species as does growth and adaptability. Frequently, trees do not produce the same wood properties when grown in considerably different environment and the wood variation is greater in exotics because of the more extreme environments under which the trees are grown. Therefore, the only real way to determine the kind of wood produced by a given species outside its natural range is to grow the trees in those environment and directly determine the properties of wood produced by them (Zobel and van Buijtenen, 1989).

The research wing of the Kerala forest department has initiated several research trials at different localities in the state during various periods, mainly to evaluate growth performance of certain introduced species. The present study focuses on three such plantation grown tree species viz., nedun tree (*Pericopsis mooniana* (Thwaites) Thwaites, andaman padauk (*Pterocarpus dalbergioides* L.f) and big leaf mahogany (*Swietenia macrpohylla* Roxb.) grown under research trials of Kerala forest department. The details of the research trials conducted by the Kerala forest department are given in table 1.

Table 1. Details of sampling location at different study sites

SI No.	Name of plantation	Research range	Area (ha)	Year of planting	Age (Yrs)	Spacing	Species	Trade Name
1	Mahagony SP No.1, Dhoni	Olavakkode	0.154	1924	88	12'x6'	*Swietenia macrophylla* Roxb.	Big leaf mahogany
2	Andaman pedauk plot, Nedumpoil	Mananthavady	0.30	1954	58	8.3'x8.3'	*Pterocarpus dalbergioides* L.f	Andaman padauk
3	Nedun tree plot, Aruvakkode	Nilambur north	0.24	1926	86	6'x 6'	*Pericopsis mooniana* (Thwaites) Thwaites	Nedun tree

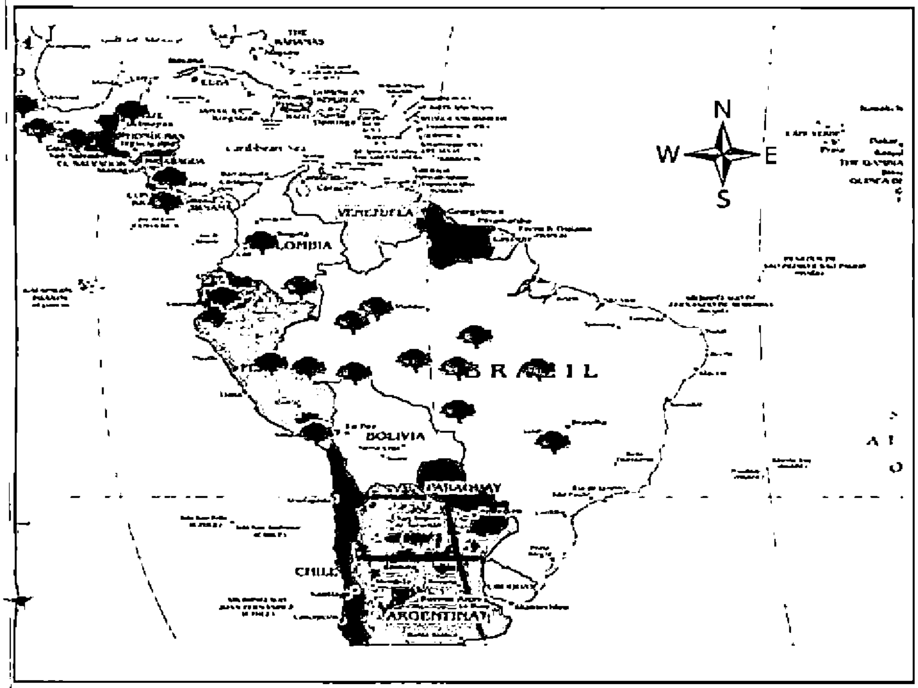
Swietenia macrophylla Roxb., commonly known as big leaf mahogany, the most important timber tree in neo-tropical forests, belongs to the family meliaceae. The natural range of mahogany (Figure 1a) extends from southern Mexico to an arc along the southern Amazon basin of Bolivia, Brazil and Peru (Lamb, 1966). In its native range, mahogany timber is still obtained from natural forests because, decades of attempts to grow the species in monospecific plantations have been largely unsuccessful owing to attacks by a shoot boring insect, *Hypsipyla grandella* (Mayhew and Newton, 1998). Continuing harvests have depended on progressive expansion into previously unlogged forests as skidding technologies changed and diameter limits dropped with changing markets, and as new sources were utilized (e.g. Brazil, Bolivia and Peru) (Grogan et al., 2002; Blundell and Rodan, 2003).

In recent years, significant quantities of mahogany entering the international trade from the Amazon region have been obtained illegally, sometimes from the lands of indigenous tribes, without their consent (Watson, 1996). As a result, the United States and some European countries froze imports of big leaf mahogany from Brazil in 2002 and the Brazilian government suspended mahogany logging (Grogan et al., 2002; Blundell and Gullison, 2003). Today, most mahogany timber in international trade comes from Peru, and most is imported by the United States. Both deforestation and timber harvesting have severely decreased the abundance of mahogany across much of its range, leading to concern about the survival of many populations of the species, as well as the sustainability of its commercial trade (Kammesheidt et al., 2001; Blundell and Rodan, 2003). As a result, in 2002, after three previous debates among the signatories, big leaf mahogany was listed in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), which calls for the scientific and management authorities of each exporting country to define sustainable levels of harvest for the species and to provide export permits accordingly (Rodan and Blundell, 2003). Since the restrictions in logging of this tree in its native habitats were imposed, it has been introduced into several Asian countries in plantation environments. The mahogany timber grown in these Asian plantations is the major source of international trade in genuine mahogany today. This tree has a relatively fast growth rate and is being used as an excellent building and furniture wood. No attempt has been made so far to study the wood quality of this species under Kerala conditions. The research wing of Kerala forest department has initiated research trials of this species from 1924 onwards at Olavakkode research range at Dhoni to evaluate the growth performance of this species.

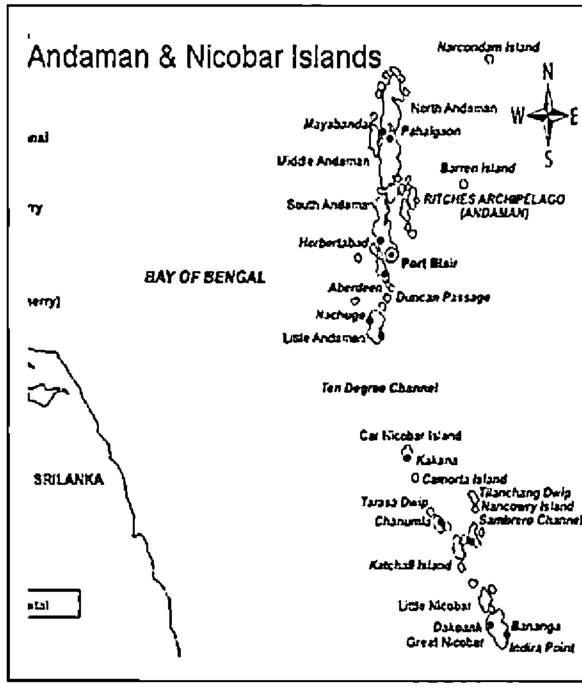
Pericopsis mooniana (Thwaites) Thwaites, commonly called as nedun tree, belongs to the family leguminosae and is generally found as an indigenous species to Sri lanka. Its native ranges distributed (Figure 1b) in South East Asian countries including Indonesia, (Irian Jaya, Jawa, Kalimantan, Maluku, Sulawesi, Sumatera), Malaysia (Peninsular malaysia, Sabah), Palau, Papua New Guinea, Philippines etc. It is threatened further by poor natural regeneration and lack of replanting. The species has been heavily exploited for its beautiful timber, which is in great demand and realizes high prices. Wood of *Pericopsis mooniana* is being used for cabinet making, furniture as well as for construction purposes.

P. mooniana has been widely planted 'off-site' by villagers on the lowland slopes and hills of tree gardens because of its desirable high quality furniture wood (Ashton et al., 1997). The species is also characterised by a clear sapwood- heartwood distinction. The wood is sometimes used as a substitute for teak. Hence it is considered to be a valuable multipurpose wood. However, the supply of the wood is very limited, because wood of this species is mainly harvested from only natural forests (Soerianegara and Lemmens, 1994). In addition, this species is considered vulnerable by the International Union for Conservation of Nature and Natural Resources (IUCN). Therefore, plantations of *P. mooniana* should be established to increase the supply of wood and to prevent this species from becoming extinct. On the other hand, for expanding the plantation of this species outside its natural range, we should know the variation of wood properties among seed sources and between trees as well. However, only few reports are available on the wood properties of this species. The species tolerate good degree of shade and thrives in areas with less amount of rainfall and offers good potential for introduction in our homesteads and other areas. A research trial was established in the Aruvakkode forest depot premises at Nilambur during 1926 from seeds obtained from Sri Lanka by the research wing of the Kerala forest department for the evaluation of its growth performance.

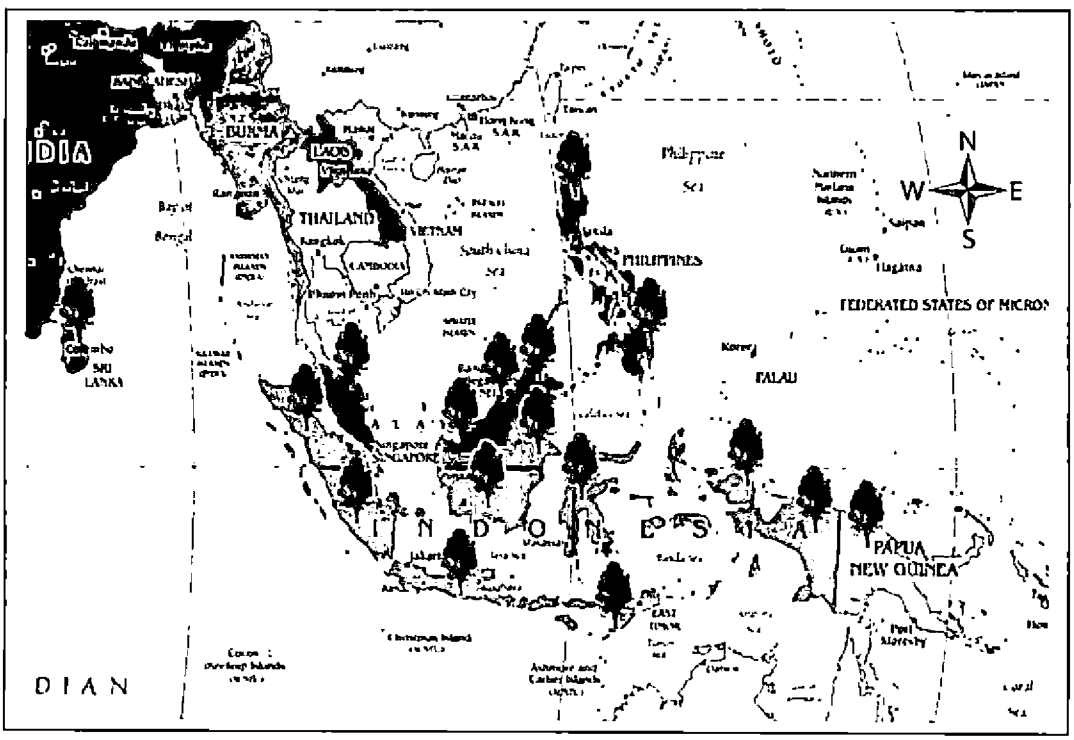
Pterocarpus dalbergioides (andaman padauk) is one of the most decorative timber species of India (Shukla et al., 1999). It is endemic and common to the deciduous and



1a- *Swietenia macrophylla*



1b- *Pterocarpus dalbergioides*



1c- *Pericopsis mooniana*

Fig 1. Map showing natural distribution of *Swietenia macrpohylla* (1a), *Pterocarpus dalbergioides* (1b) *and Pericopsis mooniana* (1c).

semi-deciduous forests of the Andaman and Nicobar Islands (Figure 1c). It is described as the principal timber tree in the island group and is usually found growing on or near riverbanks. The species is also reported to be cultivated on a small scale, mostly in gardens, in mainland India. The wood is usually pink to deep reddish brown color, hard, moderately heavy with distinct semi ring porous tendency. *Pterocarpus dalbergioides* has strong, decorative wood and is used for making high class furniture, cabinets, paneling, parqueting and for various types of decorative, marine and aircraft plywood and also for blockboard (Narayanamurti, 1956; Sekhar, 1967; Gupta, 1969). Although the rate of growth of Andaman padauk plantations is known to be faster, not much work has been carried out to evaluate its timber properties. Research plots of Andaman padauk is being maintained by the KFD research division at Manathavady research range in Nedumpoil for the evaluation of the wood qualities under the prevailing eco-climatic conditions.

With the worldwide trend towards intensive forest management to meet the wood demand and to protect the environment, wood supply around the world has undergone significant changes (Constantino and Haley, 1988; Zobel, 1984; Zhang et al., 1997). While wood supply from natural forests has declined considerably over the years, plantation forests have increased steadily worldwide and this trend is likely to continue until they predominate the world wood supply (Zobel, 1984). India has already started new initiatives for establishing plantations under various afforestation and reforestation programmes. In some regions, plantation grown trees harvested for commercial uses are composed entirely of juvenile wood (Bao and Jiang, 1994) and it differs from mature wood in a number of wood properties (Zobel and Sprague, 1998).Therefore it is expected that the fast growing short rotation plantations in India will be quite different from the natural stands. To better understand wood properties of plantation grown trees, it is important to understand the intrinsic difference in wood properties and its variation within and between trees. A better understanding of these differences in the wood properties will help manage stands for high quality wood for different end uses.

The present study on the wood quality of tree species such as *Pericopsis mooniana, Pterocarpus dalbergioides* and *Swietenia macrpohylla* raised by the forest department under various research trials is intended to bring to light their timber quality under the eco-climatic conditions prevailing in the state. Most of these species have been found to perform reasonably well under the prevailing conditions in the trials undertaken. They demonstrate an ability to survive and grow rapidly in a wide range of environment with varying soil nutrient content. These species offer tremendous potential for solid wood uses such as furniture making and as construction wood and hence, systematic studies on their timber quality aspects will help the forest department in introducing the above species on commercial scale in the homesteads and other suitable areas in the state. In addition, this study will help utilize the huge plantation resources efficiently.

Objective

The objective of the present investigation is to explore the timber quality parameters of *Pericopsis mooniana, Pterocarpus dalbergioides* and *Swietenia macrpohylla* grown in research trails of Kerala forest department at various locations. It is intended to study the variation in wood physical properties such as specific gravity, heart wood percentage, shrinkage, bark thickness, moisture content, anatomical properties including fibre morphology, ray morphology, vessel morphology, tissue proportion, tissue frequency etc and mechanical properties such as static bending test, compression parallel to grain, compression perpendicular to grain etc.(in green and dry condition) and other properties including sawn wood recovery and log volume. The study also aims at bringing to light the variation if any, of the timber quality of the above species when they are grown outside their natural home range.

The study is also expected to provide information helpful in fixing the optimum age of exploitation of different plantation grown species as well as to ascertain the most appropriate end-use with the presently available raw material as wood characteristics of plantation grown trees cannot be assumed to be the same as expected from fully mature trees of identical species grown in natural forest. Combining growth measurements with information on wood quality parameters will help in taking judicious management decisions for raising and management of these species in the state.

Review of Literature

REVIEW OF LITERATURE

Wood is the usual end product of forestry operations. Because of its importance, numerous studies have been made relative to wood properties, and the causes of wood variation. There is voluminous literature related to these subjects, but it is neither well known nor appreciated because of the confusing and contradictory nature of the literature (Downes and Raymond, 1977), making it difficult for the non-specialist to use the available information.

2.1 Different 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). Tree to tree variability is especially large, with difference within a species often under strong genetic influences. Wood property variation patterns that arise from apical or cambial aging and positional effects of the crown are regarded as intrinsic. External factors such as environment, site conditions and silvicultural treatments also have impacts on regular patterns of wood variation and these are regarded as extrinsic (Perera et al., 2012). In order to produce and use wood efficiently, the variation patterns within trees, among trees within species and among species must be understood.

Variation occurs among segments of a species that grow in different environment within a species range (Callaham, 1964; Burley and Wood, 1976). In actuality, all wood properties are determined by an interaction of the genetic potential of the tree with the environment in which the tree grows. Variability of wood gives it greater utility. But on the other hand, these wood variations results in variation in quality and thus in production inefficiency. Since a major industrial need is to have greater uniformity (Zobel et al., 1983), Larson (1969) states that the greatest wood quality problem facing all wood using industries is lack of uniformity.

There is great need for research in the area of wood variation and its control. 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 (Zobel and van Buijtenen, 1989). Intensive studies of variation within a species are necessary for tree improvement programmes to be successful. Such studies have already been made in species such as on the loblolly pine by (Thor, 1961), on virginia pine (Lamb, 1973; Barnes et al., 1977), on jack pine (Yeatman, 1967).

2.2 Wood properties of exotic hardwoods

Exotic species are being raised now a days for large scale afforestation programmes all over the country. One of the major reasons for introducing exotics is to obtain specially desired type of wood not available from the indigenous species where the exotic is to be grown (Zobel et al., 1987).

Native and exotic species have acquired commercial importance in various afforestation and reforestation projects based on the limited knowledge of their genetic, reproductive and forest plantation management. However, only little studies on the properties of few plantation grown species have been found. When wood properties were determined, they were limited to a reduced number of characteristics. For example, Butterfield et al. (1993) carried out a study on the radial variation of the basic density, fibre length and vessel area from pith to bark in *Hyeronima alchorneoides* and *Vochysia guatemalensis*, comparing trees grown in natural conditions with those grown in plantations. Gonzalez and Fisher (1998) studied the specific gravity, fibre length, vessel density and vessel radial diameter from pith to bark in natural forests of V. guatemalensis in Costa Rica, while Moya (2000) evaluated the sawmilling process of 6-year old T. amazonia trees from fast-growing plantations in Costa Rica.

The choice of plantation species for a particular end use requires consideration of many factors. In general, the choice may depend upon one or a combination of wood properties. Although the specific gravity (SG) of the wood is the most commonly studied wood property because it is a good indicator of many working properties, there are other wood properties not related to the SG that can affect end use requirements (Zobel and Van Buijtenen 1989). The remarkable difference in wood properties between species means that information about the quality and utilisation potential of promising plantation species must be taken into consideration. There is a great number of wood properties that have some influence on wood products or wood processing. However, it is necessary to first identify the main characteristics that determine the quality of the wood products (Laurila 1995).

It is generally well known that works on wood properties of hardwoods grown as exotics has been very limited except eucalyptus, when compared to that devoted to the conifers. It has been found that, wood properties of hardwoods vary greatly from tree to tree within a species and sometimes also considerably within the geographic range where the species originated or where it has been later grown as an exotic. Juvenile wood development in hardwood is found to be moderate and the variation in wood with the age of the tree is usually small. Similarly, the difference in wood properties from the base to the top of the tree are less, resulting in more uniformity within a given forest stand (Zobel and van Buijtenen, 1989).

If commercial plantations are to be established with genetically improved stock it will be essential to understand the variation in wood properties within and between species. Moreover, further research is required to adequately describe and understand the pattern of variation in wood properties with genotype, age, management and site conditions (Searle and Owen, 2005).

Wood of hardwoods vary greatly from very light and softwood of balsa to the heavy tropical woods having high specific gravity. For example, mahogany and teak have been grown quite widely in exotic plantations in several countries, however literature regarding their wood quality variation are limited. Chundnoff and Geary (1973) reported little relationship between the wood of *Swietenia macrophylla* grown in its natural range and that of progenies from the same trees in the exotic planting.

One group of trees planted extensively as exotics are the many species and hybrids within the genus Populus. Members of this genus have been planted and managed intensively for years and considerable amount of research has been done with respect to wood variability. Other tropical hardwoods that have been planted as exotics include *Albizia falcateria, Anthocephalus cadamba, Gmelina arborea, Pterocarpus dalbergioides, Pericopsis mooniana* etc.

Wood industry is slowly shifting to non - traditional raw materials due to the shortage of timber supply from traditional sources. This shift involves the establishment of tree plantations using fast-growing species. Because of high productivity, shorter rotation cycle, and multifarious end-uses, plantation species are considered a potential solution to the country's timber shortage. However, research gaps need to be addressed to maximize these species' utilization potential. Most of them present special problems as they do not have a history of utilization or may have properties different from traditional species (Jara et al., 2008).

Most plantation species that have so far been studied were found to have set backs in wood quality including low durability, low density or strength, and prone to warping and other drying related defects largely due to the high proportion of juvenile wood (Alonzo et al., 1998). These wood characteristics create challenges in processing technologies such as sawing, seasoning, and machining (Bendtsen, 1978). However, a major drawback for the promotion, management and efficient utilization of new timber species are the lack of information regarding their wood properties and wood quality when grown under local conditions. Availability of such information prior to large scale forest plantation establishment plays a crucial role in selecting the species most appropriate for the envisaged end use. Even for popular timber species such as S. macrophylla, wood property information when grown under local conditions is rare in the literature (Perera et al., 2012).

Wood quality has long been recognized as an important objective of forest genetic research, although many early tree improvement programmes did not include wood as a trait for initial selection and testing. Wood quality varies with species, provenance, tree age, site and plantation altitude for many conifers and hardwoods (Ladrach, 1986).The testing of wood is crucial when planting trees as exotic species since the quality of wood in new environments can sometimes be quite different from wood of trees grown within their natural range (Ladrach, 2000).Therefore, wood quality evaluation of the suitability of wood grown in exotic environment is essential for anticipated end uses before large scale planting is done.

2.3 Variation within and among trees

Generally, almost all trees show variation in wood qualities from the centre of the tree outward, from the base to the top of the tree, within an annual ring, and sometimes even on different sides of the tree in relation to the sun and temperature (Sluder, 1972). The differences between wood properties of trees from natural and manmade forests are associated with the short rotation and resulting high proportion of juvenile wood (Bendtsen, 1978). The within tree variation is the result of a fixed developmental pattern, which is generally difficult to change to make wood more uniform. However, the within-ring differences can be modified somewhat by controlling the growth. Another effective method for reducing variation in wood is to develop trees with uniform wood through breeding and silvicultural manipulation, including fertilization (Zobel and van Buijtenen, 1989).

2.2.1 Tree to tree variability

Generally tree to tree differences in wood properties within a species or within a provenance are large. Such variation occurs within both conifers and hardwoods and is of a great magnitude that is often greater than that between species. For example, Harris (1961) suggested that difference in specific gravity among trees of same age grown at any one site can amount to 60 percent. For *Eucalyptus camadulensis*, Chudnoff (1961) reported that, there is more variability among trees on the same site than the average differences between sites.

Variation pattern from tree to tree within a species is relatively constant from provenance to 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. McKimmy (1959) stated that tree to tree variation is so large that it commonly mask other causes of wood variability. If it is not recognised and accounted for, huge errors will be made in wood studies or in predicting strength and quality of products in wood utilization.

2.2.2 Variation of wood properties within trees

The important pattern of variability within trees generally includes within-ring difference, changes from centre of tree to the outside and differences associated with different heights in the tree. Larson (1967) stated that more variability in wood characteristics exists within a single tree, than among trees growing on the same site or between trees growing in different sites.

2.2.2.1 Wood variability within annual ring

Wood variation within an annual ring is generally known as early wood or late wood. Greater differences in wood properties including specific gravity and chemical composition were found between early wood and latewood within an annual ring than between sapwood and heartwood of the same Douglas- fir tree (Andrews, 1986). It can be the greatest source of variability in wood. Apart from early wood and late wood, transition wood forms as an intermediate stage between early wood and late wood and is responsible for much of the variation in wood properties in juvenile wood.

Compared to softwoods, hardwoods have great differences in cell type and structure within an annual ring. Ring porous hardwoods have a section of large sized vessels formed in the early part of the growing season, whereas diffuse porous hardwoods have much less within ring variability and the distribution of cell types and the characteristics of the types tend to be quite uniform throughout the ring. Distribution of cell types within the ring has a great effect up on wood properties.

Within ring variation is determined by the growth pattern within the plant and one method of modifying the within ring variability is through fertilization (Isebrands and Hunt, 1975).

2.2.2.2 Variation from tree centre to the bark

It is the best known and most studied within tree variability in wood, which is generally reflected as radial pattern of change in wood properties of juvenile and mature wood. The radial change in wood properties varies in magnitude and type in different species. For example, the change is found to become more abrupt in severe and short lived, initially fast growing species than in longer lived ones (Zobel and van Buijtenen, 1989).

2.2.2.3 Variation from the base to the top of the tree

Wood properties generally vary with differing height in the tree for many species and it may be attributed to the increase in proportion of juvenile wood in the stem from the base to the top. Analysing the longitudinal pattern of variation in juvenile and mature wood separately is needed for a clear understanding of changes of wood properties with the height of the tree (Zobel and Van Buijtenen, 1989.

2.3 Wood variation related to species and provenance in plantation grown trees

Generally wood of natural stands vary by latitude, elevation, soil, rainfall differences etc within the species range. Wood characteristics will also vary within the range of a species as well as those introduced in new environment as exotics. It does not produce the same wood properties when grown under differing environments. Talbert and Jett (1981) suggested that, 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. 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. Wood variation is found to be greater in exotics because of the more extreme environment under which the trees are grown.

2.4 IMPORTANT WOOD PROPERTIES

2.4.1 PHYSICAL PROPERTIES

2.4.1.1 Specific gravity

Specific gravity reflects 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). It can be considered as a reliable index of wood quality. Wood density is one of the important factor that determines the economic utility of wood for paper and pulp making as well as for solid wood purposes. Basic density is also used to estimate carbon stored in the woody stems of trees (Ilic et al., 2000) and has an appreciable influence on many solid wood properties and conversion processes, including cutting, gluing, finishing, rate of drying and paper making

van Buijtenen (1982) and Bamber and Burley (1983), state that, of all of the wood properties, density is the most significant in determining the end use of the wood. Wood density is correlated with strength properties of wood, pulp yield and pulp quality. Uniform wood density is the most important wood quality trait to include in a tree improvement programme for pulp production or for solid wood products. In hardwood species, stiffness and strength are strongly influenced 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).

Relative ease of measurement and generally high heritability makes specific gravity, most studied wood characteristic in eucalypts (Rudman, 1970; Borralho, 1992; Chafe, 1994). In general, density in eucalypts has been reported to be under strong genetic control (Zobel and Jett, 1995), withindividual 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).

The specific gravity of 220 woody species, half of them from a tropical rainforest, half from a tropical deciduous forest was studied by Morales (1987), showed a highly significant difference in specific gravity between species from the two areas and it was also found that wood from the dry deciduous forest tend to be much heavier than those from the rainforest. The specific gravity of wood showed considerable difference between species within each region and between the two regions. Trees from the drier region showed a higher average density (average 0.78) than that of trees from the more humid region. Barnes et al. (1977) in his work especially aimed at elucidating the relationship between wood density and humidity in *Pinus caribea*, reported an 88percent correlation between wood density and soil moisture deficit. Plumptre (1984) found that the wood of *P. caribaea* (at low altitudes and latitudes with a high moisture deficit or in climates with a pronounced drought had a higher density. All these studies proved the high correlation between humidity and wood structure and therefore density.

Chudonff and Geary (1973) studied relationship between wood of big leaf mahogany grown in its natural range and that of progenies from the same trees in the exotic plantings. In four test environments, specific gravity of the progeny varied only from 0.50 to 0.54 from parents which had a spread in specific gravity from 0.48 to 0.84, indicating the effect of the climate where the exotics were grown. Similarly, Scott and MacGregor (1952) analysed specific gravity variation in teak, and showed that, teak (*Tectona grandis*) seed from Burma, grown in Trinidad, produced trees with lower specific gravity than indigenous teak. It has been also suggested that, growth rate difference probably accounted for the specific gravity variation rather than the source of seed. The study conducted by Sahri et al. (1998) in *Acacia mangium* and *Acacia auriculiformis* from different provenances revealed that specific gravity and mechanical properties of the sample trees were affected by species, provinces and site.

Negative correlations between mean growth rate per species and wood density have been observed in a number of tropical forests (Enquist et al., 1999; Landau, 2004). Growth rates may increase with decreasing wood density because, (a) species with low density wood tend to be less shade tolerant and are therefore restricted to brighter than average microsites;

(b) the thickness of the peripheral shell of stem wood corresponding to a given biomass increment is inversely proportional to wood density, so that diameter growth rates vary inversely with wood density, all else being equal (c) light wooded species require less biomass to support their crowns, i.e. they have lower support costs, and are therefore able to achieve greater crown extension per unit of synthesized biomass, which enhances future light interception and growth. Light demanding species often have low density wood and tend to be more susceptible to breakage and uprooting (Putz et al., 1983). However, such differences in safety factors are due to the combined effects of differences in stem diameter and the density and mechanical properties of wood (King, 1981).

King et al. (2006) studied the role of wood density and stem support costs in the growth and mortality of tropical trees. The result revealed that, the rapid growth rates of light demanding tree species have been attributed in part to their low density, low cost stems. It was also found that, the species showed a threefold range in support cost, which was highly correlated with wood density. This relationship is due to the high interspecific variation in wood density and the fact that the stem diameter of the standard sized tree increased only slightly with decreasing wood density, i.e. light wooded species did not compensate for their lighter, weaker wood by substantially increasing stem thickness. These results suggest an important role for wood density and support costs in the classic tradeoff between rapid growth and increased risks of damage and death.

Bosman (1997) studied specific gravity variation in six year old plantations of red meranti (*Shorea leprosula, S horea parvifolia and Shorea pauciflora)* and found that the highest values were found for *S. pauciflora* (0.31), with values of 0.26 for *S. leprosula*, and 0.27 for *S. parvifolia.* Analysis of variance of the specific gravity of all studied species showed that the differences within the species are significantly larger than the differences between species. Through his studies it was also found that, there will not be any significant correlation between specific gravity and height or diameter, suggesting absence of apparent correlation between specific gravity and growth rate. But it was in contradiction with many other studies , which proved a correlation between specific gravity and radial growth rate, although this may depend upon species (Taylor and Wooten, 1973; Land et al., 1983; Zobel and van Buijtenen,1989; Sedenio, 1991; Castro et al.,1993).

The pattern of distribution of specific gravity showed that there were low and high specific gravity zones in the stem. The calculation of change in specific gravity with tree aging suggests that clones with high specific gravity can be selected at an early stage. Growth rate does not affect specific gravity. Growth rate and specific gravity are the main traits to consider in clone selection to improve wood quality in natural acacia hybrid (Kim et al., 2008).

High variation in specific gravity from the base to top and or from pith to bark can affect yield and quality of pulp and solid wood products. Much of the breeding for wood density is primarily aimed at producing more uniform wood, as desired by the processors and manufacturers of wood products (Zobel and Jett, 1985). An understanding of the patterns of variation within trees could have impacts on product quality, optimum harvest age and how trees are processed at the mill.

2.4.1.1.1 Radial variation in specific gravity

Variation of specific gravity from pith to periphery has been noticed for many species. Some species, such as *Swietenia macrophylla, Liquidambar styraciflua, Liriodendron tulipifera* and others have an increase in specific gravity from pith outward (Briscoe et al., 1963; Hunter and Goggans, 1968; van Eck and Woessner, 1964; Webb, 1964; Herpka, 1965; Slunder, 1970). The specific gravity of *Eucalyptus grandis* increased from 0.414 in the central segment to 0.472 in the outer segment along radial direction (Hans *et al.* 1972). Study of Shanavas and Kumar (2006) also proved the same result of increasing specific gravity from pith to bark in species such as *Grevellia robusta, Acacia auriculiformis and Acacia mangium.*

Yanchuk and Micko (1990) examined radial variation of wood density in fifteen genetically distinct clones of trembling aspen (*Populus fremuloides* Michx.) from natural stands in central Albena, Canada, and found a substantial variation in change of wood density occuring across the radii among clones. It was also revealed that for most of the clones, wood density was relatively high near the pith, decreased around growth rings 12-20 and, then increased.

Sharma et al. (2005) analysed the specific gravity in coppiced and non-coppiced *Eucalyptus tereticornis*. It was observed that, pith to periphery variation in specific gravity were non significant in case of non-coppiced wood whereas it was significant for coppiced wood. The trend of variation in both the cases was a decrease in specific gravity after a distance of 5cm and 7cm. Variation of wood specific gravity from from pith to bark was investigated for *Gmelina arborea* plantations in western Venezuela (Espinoza, 2004).The results showed that, there is an increase in specific gravity from pith to bark.

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). Increases in specific gravity with distance from the pith are a common trait among tropical wet forest species (Wiemann and Williamson, 1989). These increases appear to be associated with the growth strategies of trees and their environments. 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). In tropical wet, dry and montane forests specific gravity is lowest near the tree centre and increases linearly toward the periphery, sometimes without reaching an upper limit or plateau (Wiemann and Williamson 1988). In Costa Rica, dry forest species showed increases of 20-80 percent with distance from pith, montane forest species 20– 40 percent, and some tropical wet forest species had specific gravity increases of 20–270 percent (Wiemann and Williamson, 1989). Woodcock et al. (2000) found specific gravity increases of 10-40 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 (Woodcock et al., 2000). Even within a species, specific gravity may vary between wet and dry forest sites, as shown for *Ceiba pentandra* which had higher specific gravity in dry forest (Wiemann and Williamson, 1989).

The increase in specific gravity from pith to bark is especially pronounced in pioneer tree species. The colonizing habit requires rapid growth in stature which results in the production of a weak trunk early in development (Wiemann and Williamson, 1988). The tropical pioneers *Hampea appendiculata, Heliocarpus appendiculatus*, and *Ochroma pyramidale* exhibited extreme radial changes in specific gravity of 100–300 percent from pith to bark, presumably as responses to the intense competition acting upon light demanding species (Wiemann and Williamson, 1989). Saldarriaga (1987) has found that secondary succession in the northern Amazon is associated with an increase in wood specific gravity of the trees represented. It thus appears that this character may be useful in providing information about successional status of the taxa or forest types (Wheeler et al., 1995).

In nutrient rich whitewater flood plains of the Amazon River and its main tributaries, growth strategies vary from fast growing pioneers with specific gravity as low as 0.22-0.24g/cm^3 (*Pseudobombax munguba, Solanum critino*) to slow growing trees of later successional stages with high specific gravity, e.g., 0.87 g /cm^3 in *Swertzia argentea* and *Crudia amazonica* (Parolin and Ferreira, 1998). In nutrient-poor black water floodplains of the Rio Negro, fast-growing pioneers are absent, resulting in significantly higher mean specific gravity for this ecosystem. These differences indicate that the quality of the flooding rivers plays an important role in tree ecology.

2.4.1.1.2 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 van Buijtenen, 1989). Espinosa (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 withincreasing 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*.

2.4.1.2 Shrinkage

Generally wood shows a very complicated swelling or shrinkage behaviour with the adsorption or desorption of bound water below fibre saturation point. The increase or decrease of free water above fibre saturation point does not cause changes in wood dimensions. The swelling or shrinkage of wood shows anisotropy and the ratio is generally 10 (tangential): 5 (radial): 0.1–1 (longitudinal). Considerable dimensional changes that occur due to swelling or shrinkage are the cause of cracks in lumber and internal stresses and are undesirable characteristics from the point of view of timber utilization. On the other hand, swelling and shrinkage could also be considered as intelligent characteristics of wood because wood can change dimensions by itself in response to the atmosphere (Okuma, 1998). Therefore it is important to obtain accurate knowledge on the swelling and shrinkage behavior of wood.

Donaldson et al. (2004) studied shrinkage properties of compression wood in radiata pine and noticed abnormal 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., 1994). Compression wood and spiral grain 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

Sharma et al. (2005) studied shrinkage properties in coppiced *Eucalyptus tereticornis* and non-coppiced *Eucalyptus tereticornis*. He found that, the shrinkage values are comparable in both the cases and are much higher compared to teak. It was also noticed that, longitudinal shrinkage was more in coppiced wood. A few studies made earlier in *Eucalyptus tereticornis* (Jain, 1969; Kothiyal et al., 1998) indicated that shrinkage values are very high. The higher values of shrinkage are the main cause of dimensional instability of the timber from both non-coppiced and coppiced wood. One of the reasons for such high shrinkage is the occurrence of tension wood in this species (Rao and Hemavathi, 1992).

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 the 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 *Dysoxylem hamilotni* with that of teak, and showed a high value for their tangential, radial and volumetric shrinkages with respect to teak. Similar studies of shrinkage properties were studied in *Grevillea robusta* and *Terminalia myriocarpa* by Khanduri et al.(2000). They found that shrinkage values of *Grevillea robusta* and *Terminalia myriocarpa* are higher than that of teak. 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 was higher when 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.*

2.4.1.3 Bark thickness

Tree bark can comprise a large amount of the total wood volume. In North America, Heath et al. (2009) found that amount of tree bark varied by species and can range from12 to 20percent 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 11percent to a forest landowner (Marshall et al., 2006).

Earlier research on bark focused on predicting its thickness at breast height (Monserud, 1979), since total bark volume of standing trees can be roughly derived if the information of the bark thickness at breast height is available. Recently, more work has been done on predicting bark taper along tree stems (Laasasenaho et al., 2005; Maguire and Hann, 1990; Brooks and Jiang, 2009), as the bark thickness varies from the bottom to the top of the tree. A variety of other methods have also been used to predict bark thickness. 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).

Bark thickness is estimated using equations or tables that use variables such as diameter over bark, height up the tree, or total tree height. Many of the models (Gordon, 1983, Cao and Pepper, 1986, Johnson and Wood, 1987) were developed for measuring the standing volume of a tree and used independent variables such as inside bark diameter at breast height to in-crease their predictive power.

Bark thickness on a tree varies not only with species but also by the rate of growth, the genetic constitution of each tree, and position along the bole (Laasasenaho et al., 2005). Thus, one bark thickness function with the same set of parameter values cannot be unanimously applied to all trees, even for the same species. Developing a local bark thickness equation can take a significant amount of work as it is often recommended to make at least 25–50 measurements (Husch et al., 2003).

2.4.1.4 Heartwood – Sapwood ratio

Concern about environmental impacts of chemical wood preservatives has resulted in increased interest for natural wood durability. The natural durability of sapwood of most species is generally low, while heartwood can be more resistant to biodeterioration. 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). Sapwood is the living portion in wood, which is generally light coloured and less durable.

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 recently by 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. Trees with different sizes and ages can be compared.

Shukla et al. (1983) 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. Although sapwood strength is less than that of adjoining outer heartwood, there is no significant difference within the heartwood region but decreases in the sapwood region. Although sapwood strength is less than that of adjoining outer heartwood, there is no significant difference between the strength of average heartwood and sapwood.

The quantity of sapwood that a tree contains is important to physiologists (Margolis et al., 1995; Ryan et al., 1995; Becker et al., 2000), ecosystem scientists (Callaway et al.,1994; Berninger and Nikinmaa, 1997) and wood technicians (Wellwood, 1955; Tjoelker, 1990; Morrell et al., 1996; 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.

Formation of heartwood in pine species includes disappearance of stored starch in ray parenchyma cells (Frey-Wyssling and Bosshard, 1959), decrease of moisture content, closure of pits (pit aspiration) and lignification and death of parenchyma cells (Bauch et al., 1974), and deposition of extractives (Bergstrom, 2003).

Flaete and Vadla (2008) studied variation in heartwood diameter along the stem in 56 scots pines sampled from northern parts of Norway. He observed that heartwood diameter decreased from the base and upwards the stem in 49 of the trees. Seven trees deviated from this general pattern. In these trees the heartwood diameter increased from the base of the stem to a maximum at approximately 1-3 m, and then decreased towards the top.

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 that, Percentage heartwood, sampled at 20percent of tree height, ranged between 2.4 and 43.8percent for species and 0.0 and 44.1percent for provenances. There were highly significant differences between the Acacia species for percentage heartwood. There was some association between percentage heartwood and basic density at the species level but no association was found at the provenance within species level.

In many studies, sapwood area is linearly related to the distal leaf area for a given species (Margolis et al., 1995). However, the relationship often varies by growth rate (Wellwood, 1955; Albrektson, 1984; Bancalari et al., 1987), crown class (Dean and Long,1986; Thompson,1989), fertilization (Brix and Mitchell,1983), age, stand density (Keane and Weetman, 1987), elevation and geographic region (Lassen and Okkonen, 1969), climate (Mencuccini and Grace, 1995), sampling location with respect to the crown (Kershaw and Maguire, 2000), and whether the stem is self supported or leaning on another object for support (Gartner, 1991). When a tree is pruned, the sapwood area will diminish, although not necessarily in direct proportion to the loss of leaf area (Margolis et al., 1988; Langstrom and Hellqvist, 1991).

There are also numerous examples that suggest that water transport is not the only factor determining sapwood area. For example, ring porous trees often maintain many years of sapwood (Panshin and de Zeeuw, 1980), but only one or two rings provide the majority of the water transport (Ellmore and Ewers, 1986; Cermak et al., 1992). Sapwood contains an average of 20 percent air by volume (Gartner et al., 2001), and different parts of sapwood have different permeabilities, based on radial position (Comstock, 1965; Puritch, 1971; Spicer and Gartner, 2001), vertical position (Whitehead et al., 1984; Pothier et al., 1989;

Spicer and Gartner, 2001), and presence of reaction wood (Spicer and Gartner, 1998) or embolisms (Tognetti et al., 1998).

Gartner, (2002) studied sapwood quantities in Douglas fir in relation with leaf area and density. He found that the quantity of sapwood in douglas fir does not appear to be related causally to leaf area, even though the sapwood area and leaf area are correlated. The most striking pattern that emerged was that sapwood width was relatively constant from the base upward towards the tip. There were no significant correlation between sapwood width and either the average latewood density in the sapwood or the average density of the sapwood, at any heights. Sapwood varied greatly in width. For example, at the base, it varied from 2.6 to 6.5 cm in width.

There exists, wide variation of sapwood width within a species. This variation has variously been ascribed to such factors as site (Nelson, 1976), climate (Chalk, 1951), elevation (Lassen and Okkonen, 1969) and tree vigour (Wellwood and Jurazs, 1968). 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; Higgins, 1984; Wilkins, 1991). Heartwood development is linked to tree size, and even aged trees that grow more in diameter and height have more heartwood and a higher heartwood proportion in the stem (Gominho and Pereira, 2000, 2005; Gominho et al., 2001; Miranda et al., 2006).

Yang et al., 1985, established a clear relationship between sapwood width and tree age in species such as Tamarack and Jackpine whereas Todorovsky, (1966) in pine species and Smith et al. (1966) in Douglas fir could not find any positive relationship between the proportion of sapwood in a tree and its age. It is generally accepted that heartwood width is more clearly a function of tree age (Hillis and Ditchbume, 1974). A study conducted by Hazenberg and Yang, (1991) confirmed the above said results for balsam fir in sapwood/heartwood width relationships with tree age. In the study he measured five variables including number of sapwood and heartwood rings, sapwood and heartwood width and sapwood basal area. The study revealed that considerable variation existed in sapwood width, particularly during the period from 40 to 70 years at breast height age. The number of heartwood rings expanded quite rapidly to 0.81 ring per year at the cost of sapwood ring expansion which averaged 0.19 ring per year. Sapwood width also have some relationships with crown size (Grier and Waring, 1974; Kaufmann and Troendle, 1981; Keane and

Weetman, 1986; Long and Smith, 1987; Marchand, 1984).The decrease in the number of sapwood rings in a mature tree may be the result of this phenomenon. It should be noted that the transformation of sapwood into heartwood occurs continuously, regardless of the relationship between crown size and sapwood width. The formation of heartwood may exceed one ring per year after the tree reaches age.

Moya and Munoz (2010) determined 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 . It was found that, heartwood was absent only in *A. acuminate* and was found only at less than 50 percent commercial height in *B. quinata, V. guatemalensis* and *T. amazonia.* The estimation of heart wood content helps to define differences in durability and other wood characteristics (Wiemann and Williamson,1989). Low heart wood content was documented in some tropical plantation species, such as *T. grandis* (Perez and Kanninen, 2003; Moya and Perez, 2008) and *G. arborea* (Moya, 2004). The decline of the heart wood content with tree height was confirmed in previous studies on *B. quinata* (Perez et al., 2003), *A. mangium* (Lee et al., 1999) and *V. guatemalensis* (Moya et al., 2009). However, these researchers did not find the presence of heartwood in 9-year old *T. amazonia* plantations in Costa Rica. The lower heart wood content or lack of heartwood, in contrary to this results, in some fast growing tropical species shows that this tissue increases with tree age (Perez et al., 2003).

A positive variation of sapwood area with tree radial growth has been shown for *E. globulus* trees in various conditions, i.e. at different plant densities (Gominho and Pereira, 2005), in trees grown at different sites (Miranda et al., 2007), and in fertilised and irrigated trees (Miranda et al., 2006).

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. Whereas, sapwood width was relatively independent of tree dimensions which mean that, more heartwood is found in larger trees and that forest practices aiming at increasing individual tree radial growth also increase heartwood. In addition it was also revealed that spacing impacts tree dimensions and therefore heartwood quantity.ie, Trees grown with lower plant densities will have more heartwood than those grown with higher plant densities and the balance of sapwood and heartwood production on a unit area basis should be considered when planning initial spacing.

Miranda et al. (2006) reported high values of heartwood proportion at breast height, between 68 and 78 percent for 18 year old *E. globulus* trees, and data are also available for younger *E. globulus* trees: 43percent in 9 year old (Gominho and Pereira, 2000), and 29 - 61percent in 8-year old trees (Miranda et al., 2007). However, these studies indicated that it is not age but tree dimensions, particularly tree diameters that are the main factors responsible for heart-wood development. This is in agreement with similar results obtained for other eucalypts, i.e. *Eucalyptus grandis* (Wilkins, 1991) and for other species, i.e. *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), although a few authors report the inverse correlation in *Pinus silvestris*, *Picae abies* and *Cryptomeria japonica* (Karkkainen, 1972; Hillis, 1987).

The effect of spacing on heartwood development in 9 year old *E. globulus* trees was examined by Gominho and Pereira (2005), who concluded that spacing influenced heartwood content because of its impact on tree dimensions, i.e. trees grown at higher plant densities had less heartwood.

Thulasidas and Bhat (2009) compared sapwood -heartwood percentages in the 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.

2.4.2 ANATOMICAL PROPERTIES

Variation of anatomical properties of wood within the main stem of a tree is often quite large, and has been shown to be strongly related to proximity of the crown during wood formation (Larson, 1960, 1962, 1964; Isebrands, 1972). It is well known that both environmental and genetic factors are involved in the process of wood formation and that the anatomical properties can be influenced to different degrees by each of the factors. Almost all anatomical parameters will vary significantly from the pith outwards within a tree. Various wood anatomical properties can be used to differentiate between juvenile and mature wood (Bhat et al., 2001).

2.4.2.1 Vessel morphology

Vessel morphology is substantially influenced by environment. It could be useful as a proxy for soil water salinity in the case of mangrove species. Schmitz et al. (2006) studied influence of salinity gradient on the vessel characters of mangrove species, and reported a significant positive correlation between vessel density and salinity for the rainy (earlywood) as well as for the dry season (latewood). A distinctly lower vessel density was recorded at the sites with low salinity, relative to the site with high salinity. Vessel area and distribution are important determinants of the suitability of hardwoods for pulping. Vessels were reported to be absent at the beginning of growth rings of *Eucalyptus nitens* (Sandercock et al.,1995), *E. regnans* (Bisset and Dadswell, 1950) and *E. delegatensis* (Amos et al., 1950). In *E. delegatensis*, Dadswell (1972) reported the absence of vessels in latewood and first formed earlywood. Vessel numbers were reported to be lower in the latewood of *E.* nitens, *E. globulus* and *E. regnans* (Williams, 1994). In a study of 30 year old *E. pilularis*, Bamber and Curtin (1974) showed that, while vessel diameter increased with age, vessel frequency decreased. Despite the decrease in vessel frequency, it was found that vessel area increased from 7.9 percent in ring 1 to 11.9 percent in ring 30. In a study of 8.5 year old *E. nitens*, Mc Kimm and Ilic (1987) showed that vessel frequency initially decreased with increasing distance from the pith before becoming constant. Fast grown 2.5 year old *E. grandis* trees had smaller and fewer vessels and increased ray area compared with normally grown trees (Bamber et al., 1982). Another study on *E. grandis* was contradictory to his, showing increased vessel volume and decreased ray volume in fast grown trees (Malan,1988).

Vessel lumen diameter (VLD) is another important anatomical property. Vessel lumen diameter generally shows a juvenile to mature pattern of variation from the pith to the bark (radial variation), where vessel lumen diameter is smaller in the inner part of stem, and gradually increases in size outwards before levelling off in the outer part of the stem (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). A study on the relationship between the radial variation in vessel lumen diameter and the stages of the radial growth in species such as *Castanea crenata, Quercus serrata, Populus simonii and P. beijingensis* showed that vessel lumen diameter increased in size during the early and the middle stage, and stabilized in the late stage (Tsuchiya

and Furukawa, 2008, 2009). An important factor potentially interfering with ecological trend in vessel diameter is age (Corcuera et al., 2004). To maintain a favourable water balance, when the tree is growing and increasing its leaf surface, trees usually produce longer and wider vessels in their stems with age (Tyree and Ewers, 1991; Hudson et al., 1998; Cruiziat et al., 2002.)

Studies by Carlquist (1966) and Zhang et al. (1988) showed that vessel diameter and vessel element length decrease with increasing aridity and that of vessel numbers increase. This view is also supported by the work of Tyree et al. (1994) which showed that, while vessel efficiency increases with vessel diameter, safety of the transpiration system increases with decrease in vessel diameter and increase in vessel numbers. Xylem vessels with bimodal diameter distribution offer the advantage of an efficient (large vessels) and safe (small vessels) water transport system (Mauseth and Stevenson, 2004). The functional benefits of this vessel combination explains its frequent occurrence in the flora of arid regions (Baas et al., 1983; Baas and Schweingruber, 1987; Villagra and Junent, 1997).

February et al. (1995) examined the relationship of xylem vessel diameter, vessel frequency and vessel element length with water consumption in *Eucalyptus grandis* and two hybrids. It was found that in *E. grandis* and the hybrid *E. grandis* x *E. camaldulensis* vessel diameter ($P<0.01$ and $P < 0.05$ respectively) and vessel element length ($P < 0.05$ for both) increased from the dry to the wet treatment as water uptake through transpiration increased. There was no significant correlation between available water and vessel frequency. For *E. grandis* x *E. nitens*, on the other hand, only vessel frequency was significantly ($P < 0.01$) correlated with water uptake. These results suggest that *E. grandis* x nitens may be more water use efficient than E. grandis, which is commonly grown for timber and thus could potentially be used as a replacement species that is more water conservative in this water limited region. 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). Within a tree, vessel diameters tend to be greater in roots than in stems, and greater in the stem than in branches. Vessel diameter usually increases from pith to bark (Zimmermann, 1978, 1983). Previous research has shown that, in general, vessel diameters and vessel element lengths decrease while vessel frequencies increase with increasing aridity. Zhang et al. (1988) showed a strong positive correlation between rainfall, altitude and element size in *Syringa oblata*, Wilkins and Papassotiriou (1989) indicated a trend towards decreasing vessel diameter with increasing dryness for *Acacia melanoxylon* and February (1993) demonstrated a strong correlation between rainfall, vessel diameter and vessel frequency in *Combretum apiculatum* and *Protea caffra*.

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. Bissing (1982), through his studies clarified the role of the habitat as a modifier of wood structure. He found that some characters like porosity, pore frequency and diameter and grouping frequency vary according to water availability. Baas et al. (1983) stated that in the arid flora of Israel, vessel elements tend to have thicker walls, smaller diameter, and be more crowded, characters that would lead us to expect a higher specific gravity in the wood of species from that region. Outer and Veenendaal (1976) compared savanna species with those of a rainforest and found no significant differences in length and diameter of vessel elements. However, they found significant differences in height, width and abundance of rays and in pore abundance. Vessel property variation in *Eucalyptus globulus* and *Eucalyptus nitens* were studied by Hudson et al. (1998), showed that individual vessel areas increase and vessel numbers decrease from pith to bark in both *E. globulus* and *E. nitens*. It was also found that, total vessel area increases slowly across the disc, but was markedly influenced by position within annual rings, decreasing from latewood (LW) to first early wood (EW); increasing in mid wood (MW) and then decreasing from mid wood to latewood. It was also found that, vessel morphology follow an EW, mid wood and LW segmentation in both *E. globulus* and *E. nitens*. The transition to late wood vessel was synchronous with the transition to latewood fibres. From early wood to mid wood, vessel frequency (per mm^2) significantly increases (1 to 2 fold), as does vessel percentage coverage (total vessel area/ total segment area) (1.5 to 2 fold). Moreover, vessel frequency and percentage coverage in latewood are significantly less (50 percent less) than vessels in mid wood at 5 percent height.

According to Sharma et al. (2005), vessel diameter showed an increasing trend in *Eucalyptus tereticornis* while the vessel element length did not show any definite trend from the pith outwards in both non-coppiced and coppiced wood. Adamopoulos and Voulgaridis (2002), studied within tree variation in the cell dimensions in the wood of Black locust (*Robinia pseudoacacia*).They found that mean vessel member length was higher in latewood than in early wood while the reverse occurred in the case of vessel member diameter. For early wood, vessel member length and diameter were found to be 0.16 mm and 47 μm, respectively and for latewood, mean vessel member length and diameter were 0.18 mm and 24 μm, respectively.

Ishiguru et al. (2011) studied radial variation of anatomical characteristics in plantation grown Nedun tree, and revealed that values for the vessel diameter, from wood at the bark side were higher than those at the pith side. On the other hand, vessel frequency gradually decreased from pith to bark. In addition, vessel element length showed almost constant values from pith to bark. Ogata et al. (2008) reported the values for vessel diameter, vessel frequency, in *P. mooniana.*

Generally, vessel member length of early wood and late wood has a small radial change. Hejnowicz and Hejnowizc (1959) and Furukawa et al. (1983) have made the same observation. With regard to ring porous species, a study in ash (*Fraxinus excelsior* L.) has shown that early wood vessel members showed a similar pattern of length variation, but latewood vessel members did not show such a trend (Bosshard, 1983).

Tu Kim (2008) studied anatomical variation of six natural acacia hybrid clones in northern Vietnam. It was observed that, mean length of vessel elements ranged from 0.11 to 0.12 mm in the six clones studied. Vessel element length in six clones increased marginally from 0.11 mm near the pith to 0.13 mm near the bark. Fibre length was 0.5 mm in the vicinity of the pith, reaching a maximum value of 1.1–1.2 mm close to the bark.

2.4.2.2 Fibre morphogy

Sharma et al. (2005) studied anatomical property variation in coppiced and non-coppiced *Eucalyptus tereticornis.* It was found that in both cases fibre length was correlated to fibre wall thickness and vessel diameter. In the case of fibre length, fibre diameter and double wall thickness the trend increased from the pith outwards, whereas in the case of fibre lumen diameter the trend showed a decrease towards the periphery.

Yanchuk and Micko (1990) examined radial variation in fibre length in fifteen genetically distinct clones of trembling aspen (*Populus fremuloides* Michx.) from natural stands in central Albena, Canada, and found that substantial changes occurred in fibre length across the radii among the clones. The most obvious difference, when comparing fibre length variation to wood density variation, is the general lack of variability in the pattern of radial change among clones for fibre length. Clonal differences in fibre length, based on analysis of variance were significant (Yanchuk et al., 1983, 1984). Even though in almost all cases fibre length steadily increases across the pith with very little fluctuation, it does not vary as much as wood density in the patterns of variation across the radius. Radial and longitudinal variation in fibre wall percentages in six year old plantations of red meranti (Shorea *leprosula, Shorea parvifolia and Shorea pauciflora)* were studied by Bosman (1997) showed that variation of those properties within the tree appeared small and did not show a consistent pattern. More over the variance between trees of a species however is significantly larger than the variance within the trees and that among the trees.

Ishiguru et al. (2011) studied radial variation of anatomical characteristics in *Pericopsis mooniana*, and observed higher values for fibre length and fibre wall thickness at the bark side than those at the pith side. In addition, the cell diameter of wood fibres showed almost constant values from pith to bark. Ogata et al. (2008) reported values for fibre length, fibre cell diameter, fibre cell wall thickness, as 1.0–1.7mm, 15–20μm, 3.5μm, respectively, in *P. mooniana.*

Adamopoulos and Voulgaridis (2002), studied within tree variation in the cell dimensions in the wood of Black locust (*Robinia pseudoacacia*) and found that, mean fibre length was higher in latewood than in early wood. For early wood, mean fibre length value was 0.74 mm and for latewood, mean fibre length 1.04 mm. Hejnowicz and Hejnowicz (1959) also reported longer fibres in late wood than in early wood in this species but such differences did not appear for vessel member length in their study. Cell dimensions varied significantly between the trees examined for mean early wood and latewood values. This radial variation in cell morphology refers to the general pattern that occurs in most softwood for tracheids and hardwoods for fibres, which suggests an influence of age on wood structure

(Panshin and de Zeeuw, 1980; Tsoumis, 1991). Fibre length of early wood and late wood increased from pith to bark, as also reported by other authors (Hejnowicz and Hejnowizc, 1959; Furukawa et al., 1983; Stringer and Olson, 1987). Tu Kim (2008) studied anatomical variation of six natural acacia hybrid clones in northern Vietnam and showed that, the fibre length was 0.5 mm in the vicinity of the pith, reaching a maximum value of 1.1–1.2 mm close to the bark.

2.4.2.2.1 Importance of ray and fibre morphology

In hardwoods both vessel elements and fibre morphology affect processing of wood for paper making, composite products and preserved timber products (Amidon, 1981). Environmental influences, genetic engineering, silviculture and treatment with plant growth substances may affect vessel and fibre morphology. Any selection or modification processes require an understanding of the patterns of variation in untreated trees on a whole tree basis. Spatial whole tree maps of both vessel and fibre morphology will help clarify both radial and longitudinal variation in vessel and fibre morphology and establish whether vessel distribution and size characteristics conform to the same sort of early wood, mid wood and latewood variation as described for fibres by Hudson et al. (1995) or otherwise.

2.4.3 MECHANICAL PROPERTIES

Mechanical properties of wood are those that indicates the ability of wood to resist various types of external forces, static or dynamic that may act upon it. The type of deformation, whether in size or in shape, caused in wood when it is subjected to external forces, depends on such mechanical properties as modulus of elasticity, ultimate stress, fibre stress at elastic limit etc., which are inherent in wood. These properties, however vary not only with species, with reference to the nature of their fibre structure, but also with the moisture content, temperature and defects of the woods subjected to the forces. For example, the fibres, and probably to some extent the ground tissue parenchyma which may be strongly lignified must be mainly responsible for the mechanical properties in bamboos (Alvin and Murphy, 1988). Even in respect of the same species the properties vary with reference to the varying conditions of growth and methods of testing.

Shukla et al. (1994) studied variation of strength properties of Eucalyptus hybrid with age of trees from 6 to 22 years. It was found that strength increases with age from 6-14 years and thereafter the differences were not significant suggesting that mechanical maturity was achieved in about 14-15 years and it was also found that strength increases from pith to periphery within heartwood region but decreases in the sapwood region. Shukla et al. (1989) also studied the variation of strength in axial direction and did not find significant difference in strength at different heights of the tree.

Solid wood products made from the juvenile wood are lower in quality than those made from the wood produced during the mature phase of growth for many tree species (Dadswell, 1958). One reason for this lower end product quality is that juvenile wood has a significantly lower wood stiffness and strength (Dadswell, 1958). Also, knot related defects are more prevalent in juvenile wood Although much research has been done on the relationship between wood density and growth rate (Zobel and Van Buijtenen, 1989), fewer studies have explored the influence of growth rate on wood mechanical properties (Zhang, 1995). A better understanding of the mechanical properties of wood that comes from fast grown plantations are helpful for breeding programs and for efficient processing and utilization of the wood.

2.4.3.1 Static bending test

Wood stiffness (modulus of elasticity, MOE) and strength (modulus of rupture, MOR) are important properties for structural and semi structural wood products (Raymond, 2002; Walker, 2006). These applications are subject to loads and should therefore have a sufficient strength to guarantee the desired level of structural safety and sufficient stiffness to meet the stability requirements (Kliger et al., 1998).

To evaluate the static deformation and strength properties of wood, three-point bending tests are often conducted because of their simplicity and the many occasions where structural materials are subjected to a bending load in practical applications. However, the bending tests often seem to be undertaken without considering the loading condition carefully (Yoshihara and Fukuda, 1998). According to several studies on advanced materials such as carbon fibre reinforced plastics (CFRP) and glass fibre reinforced plastics (GFRP), the loading condition has a serious influence on the bending properties. The influence of the loading conditions should be considered more carefully in the bending tests of wood. Yoshihara and Fukuda (1998) conducted three point bending tests by changing the condition at the loading point on Yellow poplar (*Liriodendron tulipfera* L.) and examined the influence of the loading conditions on the measurement of bending properties. The result revealed that when the specimen had a high depth/span ratio, the bending strength increased with the increase in the radius of the loading nose. However, the influence of the radius was small when the specimen had a low depth/span ratio. There was no significant effect of the cushion sheets used here on the measurement of bending strength.

Shukla, et al. (1999) carried out a study on the physical and mechanical properties of Andaman padauk to evaluate strength properties of a 22 year old tree grown in a small scale plantation in Karnataka. The result was compared and discussed with that of teak as well as natural grown Andaman padauk. The strength properties of plantation grown Andaman padauk viz., MOE, MOR, FS at LP and MCS parallel to grain are lower than that of natural grown timber of same species and also that of teak. The plantation grown Andaman padauk has shown lower values of strength properties as compared to natural grown ones (Limaye, 1933).

Langbour et al. (2008) conducted a study in well managed *Swietenia macrophylla* plantations of Caribbea including the Martinique. The aim of this study was to compare the major physical and mechanical properties of *Swietenia macrophylla* wood from plantations in Martinique with data on wood from natural forest stands. Results showed that the reference physical and mechanical properties measured in the samples from the 24 plantation trees were of less value than those of wood from natural forest stands, with the exception of the longitudinal elasticity modulus. These results do not affect the suitability of the wood for carpentry and cabinet making, and trees felled for thinning can be used for construction timber.

Studies on strength properties in some agroforestry tree species by Shanavas and Kumar, (2006) showed that fibre stress at limit of proportionality, modulus of elasticity and modulus of rupture values were higher for *Acacia auriculiformis*, followed by *Acacia mangium* and *Grevillia robusta*. FS at LP increased significantly from inner to outer position along the radial direction in *A. Mangium, A. auriculiformis* specimens from the outer position showed particularly high MOE compared to its middle and inner positions.

Khanduri et al. (2000) assessed mechanical properties of plantation grown *Grevillea robusta* and *Terminalia myriocarpa* and compared them with the corresponding strength parameters of teak. The results revealed that the MOR and MOE values in bending of

Grevillea robusta and *Terminalia myriocarpa* were higher than the minimum required for structural use (MOR≥425kg/sq. cm and MOE≥56000kg/sq. cm).

Ishiguru et al. (2011) studied radial variation in strength properties of plantation grown *Pericopsis mooniana* in Indonesia. He found that, modulus of elasticity, and modulus of rupture from wood at the bark side were higher than those at the pith side.

2.4.3.2 Compression parallel to grain

The properties determined under this test are useful for design of columns and evaluating suitability of timber species for post and other industrial purposes where forces act in a direction parallel to the grain of the timber (Sekhar, 1988). Kolin (1988) investigated compression strength parallel to grain in woods of *Fagus sylvatica*, *Quercus pedunculata*, poplar, fir and spruce at different moisture content of 4percent to 24percent and at different temperature between 20^0C and 80^0C. It was found that compression strength decreased with increase in moisture content and temperature. Strength properties in coppiced and non-coppiced *Eucalyputs tereticornis* were studied by Sharma et al. (2005). The study showed that values of maximum crushing stress was higher in non-coppiced eucalyptus (324/cm^2) than the coppiced eucalyptus species (276/cm^2) but less than that of teak (377/cm^2). Strength property studies conducted by Shanavas and Kumar (2006) in species such as *Acacia auriculiformis*, *Acacia mangium* and *Grevillia robu*sta analysed values of compressive stress at limit of proportionality, compressive stress at maximum load (CS at ML), and modulus of elasticity (MOE) in compression parallel to grain and revealed that, all the values were highest for *A. auriculiformis*. The significant interaction effect of species with reference to its positon indicated that CS at LP and ML, and MOE increased from inner to outer tissues in *A. mangium* and decreased progressively from from inner to outer position in *G. robusta*. Studies of Khanduri et al. (2000) on strength properties of two plantation grown species of *Grevillea robusta* and *Terminalia myriocarpa* showed higher values for compressive stress at elasic limit, maximum crushing stress and MOE at oven-dry condition than in the green condition and showed that all the values were very low compared to the corresponding strength values of teak.

2.4.3.3 Compression perpendicular to grain

The properties evaluated under this test are useful for selecting timber species for uses where timber is loaded on its lateral surfaces such as railway sleeper, furniture, instruments and some types of sports goods (Sekhar, 1988). Shukla et al. (1994) analysed strength properties in Eucalyptus hybrid at different ages and at different height levels. It was noticed from the study that compressive stress perpendicular to grain at limit of proportionality was maximum at ground level and thereafter it declined and then values remained more or less steady. Studies by Sharma et al. (2005) showed that crushing stress at elastic limit were higher in non-coppiced *Eucalyptus tereticornis* than that of coppiced eucalyptus. Strength studies on some of the agroforestry tree species carried out by Shanavas and Kumar (2006) showed that species effect on compressive stress at limit of proportionality (CS at LP), compressive stress at maximum load (CS at ML) and modulus of elasticity (MOE) in compression perpendicular to grain were remarkable. CS at LP, CS at ML and MOE increased from inner to outer positions in *A. mangium* In *Acacia auriculiformis*, all those values increased modestly from inner to middle positions and showed a decreasing trend. Shukla and Lal (1999), studied strength properties of *Ailanthus excelsa* and compared the values with that of *Ailanthus integrifolia* and teak. The result concluded that the values of compressive stress at elastic limit in the compression perpendicular to the grain test were higher in the air- dry condition than at green condition for all the three species. Within the air dry condition values of compressive stress at elastic limit were in the order of Teak>A. integrifolia>A. excelsa.

2.5 Interrelationship between physical, mechanical and anatomical properties of wood

Wood characteristics, including physical, anatomical and mechanical 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 inturn 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 hardwood species, 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 suggested that, significant positive correlation exist between vessel percentage and basic density, and they also find, a significant negative correlation between fibre percentage and basic density. They did not observe significant correlation between ray parenchyma percentage and basic density, but found a significant correlation between axial parenchyma percentage and basic density. Moreover, a relatively high correlation was found between the cell wall 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 agree 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.* In his study, correlation coefficients between anatomical characteristics and specific gravity and also among the anatomical characteristics showed that the specific gravity was negatively related to fibre length and fibre diameter for coppiced wood, where as in non-coppiced wood specific gravity is negatively related to vessel diameter. Smith (1971) found a high correlation between specific gravity and fibre length in Populus.

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 (Anon, 1978; Brewbaker and Hutton, 1979) are considered to be ideal for energy production because of their dense wood with low moisture content.

Most mechanical properties of wood are closely correlated to specific gravity and density (Haygreen and Bowyer, 1996). The relationship between specific gravity and mechanical properties within a species has been studied over the decades. It has been widely assumed that wood mechanical properties are linearly related to specific gravity, and many studies reported a significant linear relationship between mechanical properties and specific gravity (Kellogg and Ifju, 1962; Liska, 1965; Pearson and Gilmore, 1971; Bendtsen and

Ethington, 1972; Schniewind and Gammon, 1983; Shepard and Shottafer, 1992; Zhang, 1992). However, a poor linear relationship between some mechanical properties and specific gravity was also noted (McAlister, 1976; Leclercq, 1980; Schniewind and Gammon, 1983). Barnett and Jeronimidis (2003) found many physical and mechanical properties, such as the shrinkage and Young's modulus, were strongly affected by basic wood properties, such as basic density and microfibril angle. Specific gravity provides a good but not always direct indication of the strength, stiffness and toughness of timber (Hillis, 1978). In general, the denser the wood of a species, the greater the mechanical properties of its clear timber (Bootle, 1983).

Zhang (1997) examined specific gravity- mechanical property relationship based on the data set of specimen tests on 16 timber species belonging to four distinct wood categories in species level. His study revealed that, specific gravity-mechanical property relationship, to a differing extent, varies with mechanical properties and wood categories. Among three mechanical properties studied, MOR was most closely and almost linearly related to specific gravity, followed by Cmax, whereas MOE was poorly and least linearly related to specific gravity. In general, the relationship between MOE and specific gravity in a species from the ring-porous category was stronger than in a species from the diffuse-porous category. In addition, MOE in a softwood species is generally less related to specific gravity as compared to a hardwood species. Yet, Cmax in a softwood species appears more closely related to specific gravity.

Any significant differences in mechanical performance between sapwood and heartwood are usually attributed to the radial changes in wood density or anatomical structure and not to whether the sample is heartwood or sapwood, per se (Panshin and De Zeeuw, 1980). Among the rare reports, Arganbright (1971), 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.

Hai et al. (2010) evaluated strength properties in *Acacia auriculiformis*, and suggested that, wood density possess a significant positive correlation with MOR but a non-significant positive correlation with MOE. The correlations between total shrinkage traits and wood mechanical properties were found to be positive but non-significant. MOE and MOR in heartwood had very strong positive correlations with MOE and MOR in sapwood. Denser wood tended to have slightly greater MOE and MOR, based on the positive genotypic correlations and the comparison between heartwood and sapwood traits for density and the mechanical properties. In addition, MOR was generally more influenced by density than MOE. Consequently, it appears that growth rate influences wood mechanical properties not solely through its effect on wood density. A similar conclusion was reached by Zhang (1995) from studies on several hardwood species including, *Betula platyphylla*, *Betula utiliz*, *Populus cathayana*, and *Populus tomentosa*. The stronger relationship between density and MOR is also supported by the earlier results reported in hardwood species (Zhang, 1995; Innes, 2007) and indicates that indirect selection of wood density is highly efficient for improving MOR.

At present, when complete results of a species are not available, the unknown properties are estimated from the strength and specific gravity relationship. For instance, Sekhar and Rawat (1959) established relationships between specific gravity and different strength properties in 140 species. Specific gravity vs. strength relationships showed better results in the case of estimation of mechanical properties under compression perpendicular to grain, hardness, shear and tension (Shukla and Rajput, 1990).

Materials and methods

MATERIALS AND METHODS

3.1. MATERIAL

The present investigation was carried out to find out the variation in wood anatomical, physical and mechanical properties in three selected plantation grown tree species; viz., andaman padauk *(Pterocarpus dalbergioides* Roxb.), big leaf mahogany (*Swietinia macrophylla* King.) and nedun tree (*Pericopsis mooniana* (Thwaites) Thwaites), raised in the research trials of the Kerala forest department at three localities, viz., Mananthavady research range at Wayanad, Olavakkode research range at Palakkad and Nilambur north research range at Nilambur districts, Kerala. Map showing the study sites are given below (Fig 2). The project was carried out in department of Wood Science, College of forestry, Kerala Agricultural University during 2010-2012.

3.1.1 Experimental site

The study material was collected from trees belonging to andaman padauk, big leaf mahogany and nedun tree grown in the research trials of Nedumpoil, Dhoni and Aruvakkode at Wayanadu, Palakkad and Nilambur, districts of Kerala respectively. The andaman padauk plantation from which sample were collected is located at Nedumpoil, in the Mananthavady research range and lies between 11^0 51'N and 75^0 45'E which experiences a mean annual rainfall of 3000-3500 mm and mean annual temperature of 13-35^0C. Forest loam is the general soil type. Mahogany plantation is located at Dhoni in the Olavakkode research range and lies between 10^0 86'N and 76^0 62'. December and January are the coldest months here, with a mean minimum temperature of about 22-23^0C and April and May are the hottest months with a maximum temperature of 35-39^0C. Average rainfall ranges between 3000 mm to 5000 mm. Generally the soil type is red soil, moderately deep to deep with distinct ABC horizons, containing varying amount of ferruginous gravels. Nedun tree plantation is located at Aruvakkode depot in Nilambur north range between 11^0 5'N and 76^0 12' E. The area experiences a mean annual rainfall of 1840 mm and mean annual temperature of 21^0C –38^0C. Laterite is the general soil type.

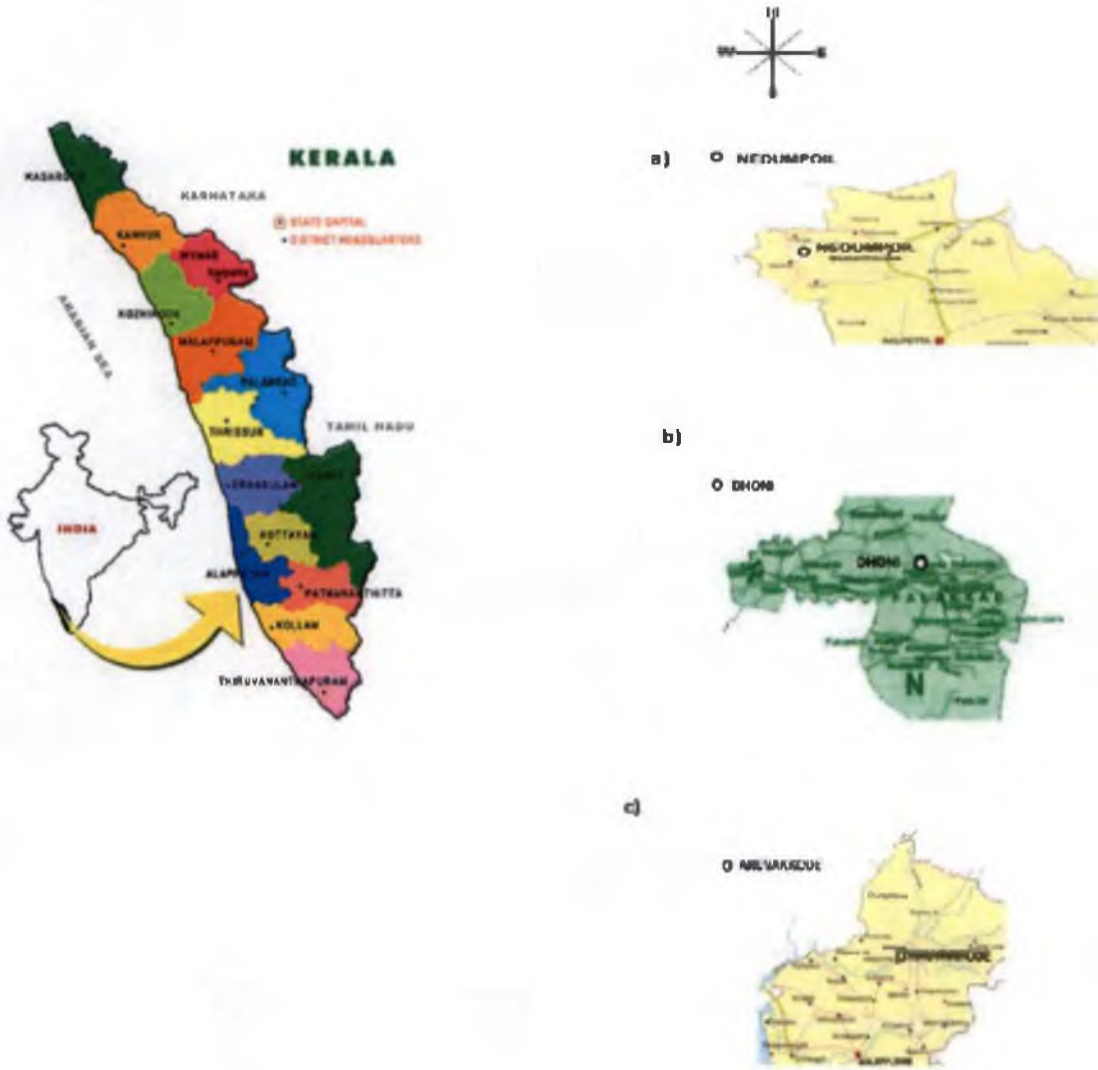


Fig. 2 Map showing the study area. a) Nedumpoil b) Aruvakkode c) Dhoni

3.2. METHODOLOGY

3.2.1. Selection of trees

Trees located at the three research plots were surveyed. Using random sampling method, five defect free trees from Mahogany plantations (Plate 1) and Andaman padauk (Plate 3), and three defect free trees from the Nedun plantation (Plate 2) were selected from Olavakkod, Nilambur, and Mananthavadi research ranges, respectively for felling. The dimensions of the selected trees for felling and further conversion into small clear specimens are furnished below.

Table 2. Details of the trees selected for felling

Sl No	Species	Tree No	Height of the tree(m)	Girth at breast height(cm)
1	Andaman padauk (*Pterocarpus dalbergioides*)	1	17.15	190
		2	11.35	142
		3	11	166
		4	13.7	166
		5	11	167
2	Mahogany (*Swietenia macrophylla*)	1	20	123
		2	18	113
		3	20	123
		4	15	110
		5	13	156
3	Nedun tree (*Pericopsis mooniana*)	1	16	103
		2	18	94
		3	15	97

Plate1. Mahogany plantation at Dhoni

Plate 2. Nedun tree plantation at Aruvakkode

Plate 3. Andaman padauk plantation at Nedumpoyil

3.2.2. Felling and conversion of trees

The trees belonging to each species at the study sites were selected randomly. After selecting the trees, different parameters such as girth at breast height (gbh) and total height were measured using tape and Haga altimeter, and a line along the side facing north of the tree was marked with paint (plate 4). Trees were felled using a chain saw. Felling and further cross cutting to log was carried out using the chain saw (plate 5 and plate 8). The basal portion of the trunks were converted to billets of 1.5m length (plate 10). Later, 5 cm thick transverse discs were cut from the base of these billets (plate 6 and plate 9). These discs were used for measuring bark thickness and to find out heartwood - sapwood percentage. The logs after cross cutting were immediately taken to the saw mill (plate11, plate 12 and plate 13) converted into scantlings of cross section 6 cm x 6 cm (plate 14 and plate 15) then, transported to the Rubber Research Institute of India (RRI), Kottayam for assessing mechanical properties. For this purpose the billets were sawn to scantlings having cross sectional area of 2 cm x 2 cm. These were finally converted to small clear specimens as per IS 2455: 1990 (ISI, 1990) for analysing mechanical properties.

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). 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 24).The converted core samples from each tree representing pith, middle and periphery were used for specific gravity measurements. Specific gravity was estimated on fresh weight, air dry and oven dry basis.

To obtain fresh weight specific gravity, the samples were weighed first immediately after conversion and the reading from the specific gravity module was also taken after putting the same sample in water. Similar observations were repeated in the wood samples

Plate 4. Marking sample trees of Andaman padauk prior to felling

Plate 5. Felling of Andaman padauk in progress

Plate 6. A disc cut out from the felled Andaman padauk log

Plate 7. Conversion of logs to small clear specimen as per IS2455

Plate 8. Felling of Nedun trees in progress

Plate 9. Discs of Nedun tree showing heartwood - sapwood variation

Plate 10. Cross cutting of mahogany trees after felling

Plate 11. Billets cut from mahogany logs

Plate 12. Billets of Andaman padauk after cross cutting

Plate 13. Billets of nedun trees after cross cutting

Plate 14. Scantlings (6 cm x 6 cm cross section) of nedun tree

Plate 15. Scantlings (6 cm x 6 cm cross section) of mahogany

Plate 16. Measurement of bark thickness using digital vernier calliper

Plate 17. Wooden blocks (3cm x 3 cm x 3 cm) of nedun tree used for specific gravity analysis

Plate 18. Measurement of radial length for assessing shrinkage using vernier calliper

Plate 19. Measurement of mid girth of Andaman padauk logs for assessing log volume

Plate 20. Collection of increment core samples using Haglf increment borer (CO1512) for studying anatomical parameters

Plate 21. Increment core being extracted from a nedun tree

Plate 22. Wooden blocks of Andaman padauk showing a) pith, b) middle and c) periphery positions used for sectioning

Plate 23. Sliding wood microtome (Leica SM 2000R) used for sectioning

Plate 24. Specific gravity module attached to an electronic balance

Plate 25. Image Analyser (Labomed Digi-2) used for anatomical quantification

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 $102^0C \pm 1^0C$, for such a time as is needed to make its weight constant.

3.3.2. Heartwood percentage

In order to assess heartwood - sapwood percentage, 5cm thick cross- sectional discs from each log were removed at breast height (1.37 m) from the three study sites. Percentage of heart wood and sap wood was determined based on the colour differentiation of inner and outer zone of the disc. Both heart wood and sapwood portions were traced using through a tracing sheet and area was calculated by using a graph paper.

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 18). 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 and tangential shrinkage (percentages) were calculated using the following formula:

Radial or tangential shrinkage from green to air-dry condition (%) $= \frac{Lg-La \times 100}{Lg}$

Radial or tangential shrinkages from air-dry to oven-dry condition (%) $= \frac{La-Lo \times 100}{Lo}$

Radial or tangential shrinkages from green to oven-dry condition (%) = $\underline{Lg-Lo \times 100}$

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 collected wood discs were measured at their major and minor axes using a vernier calliper (plate 16) and their averages were calculated.

3.3.5 Sawn wood recovery rate

For the estimation of sawn wood recovery rate or percentage, the logs collected from the three study sites were transported and processed in the saw mill. The basal butt log of 1m length was used for estimating sawn wood recovery. Mid girth of the log was measured before processing (plate 19). The method of flat sawing (tangential sawing) was adopted to achieve the maximum recovery rate. Sawn timber output (in m^3) and recovery percentage (ratio of sawn timber output over log volume) were calculated based on the commercial quarter girth formulae recommended in Indian standard specification (Thulasidas and Bhat, 2009).

3.4 ANATOMICAL PROPERTIES

Increment core samples collected at 1.73 m from the base (plate 20 and plate 21) as well as cubical wood block of dimension 2 cm x 2 cm x 2 cm (plate 22) from the three tree species were divided into pith, middle and periphery portion. A total of three blocks representing three regions of wood from each tree were used for the entire anatomical studies.

3.4.1. Microtomy

Small blocks prepared out from the increment cores samples 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 23).

3.4.1.1 Maceration

Maceration of wood samples were done using Jeffrey's method (Sass, 1971) Jeffrey's solution was prepared by mixing equal volumes of 10% potassium dichromate and 10% nitric acid. Wood shavings were taken from the $1cm^3$ wood blocks from the pith, middle and the periphery portion of the wood blocks. These chips were boiled in Jeffrey's solution for 10-15 minutes until the fibre becomes separated. After that, the test tubes were kept intact for 5-10 minutes, so that the fibers settled in the bottom of the tube. The surface solution was discarded and the remaining fibre in the tube was washed thoroughly with distilled water. This process was repeated until the traces of acid were removed. Separated fibres were stained using saffranin and mounted on temporary slides using glycerine as the mountant.

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 70percent, 90 percent, and 95 percent 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 DPX as the mountant.

3.4.1.3 Image analysis

Permanent slides were examined using an Image Analyser (Labomed-Digi 2; plate 25) 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). Images captured using this software are depicted in plate30 and plate31.

3.4.1.4 Observations

Various parameters of vessels, fibres and rays including their length, diameter and number per unit area were noted from the image using the computer software (Labomed Digi Pro-2). Each of the above measurements were repeated five times as replicates from the pith, middle and in the periphery section and is expressed was micrometers (μm).

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 2 and was expressed in number per millimetres (mm). Tissue proportion including the axial and ray parenchyma were determined from the transverse section by drawing a line on the image and counting their number along the line. It was expressed on a percentage basis.

3.5 MECHANICAL PROPERTIES

Wood samples of andaman padauk, mahogany and nedun collected from the proposed study sites were tested for their strength in the Central wood testing laboratory at Kottayam. The test was made as per IS 1708: 1986 (ISI, 1986). The mechanical properties studied using static bending tests, compression parallel to grain and compression perpendicular to grain. All the mechanical tests were made using an Automatic Universal Testing Mechine (UTM- Shimadzu 100KgN ; plate 26).

3.5.1 Automatic Universal Testing Machine (Shimadzu 100KgN)

It is a computerised and sophisticated version of the manual UTM. The instrument is an assemblage of different units. The testing unit consist of a jig where the samples are loaded for test and a head, whose upward or downward movement applies stress in the sample. The calibration of the instrument is controlled by a control keypad. This set up is associated with a computer system installed with software "winsoft" which sense the

Plate 26. 'Shimadzu' Universal Testing Machine (UTM)

Plate 27. Static bending test

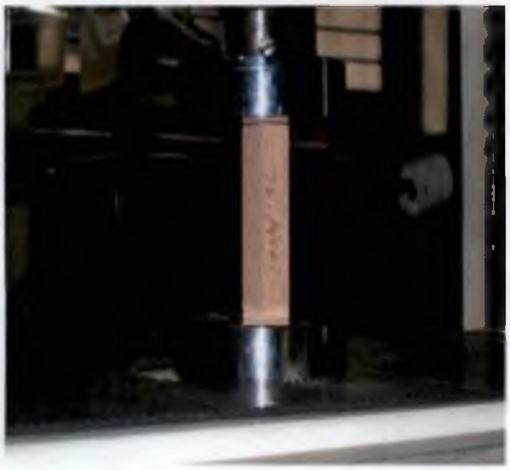


Plate 28. Test for compression strength parallel to grain

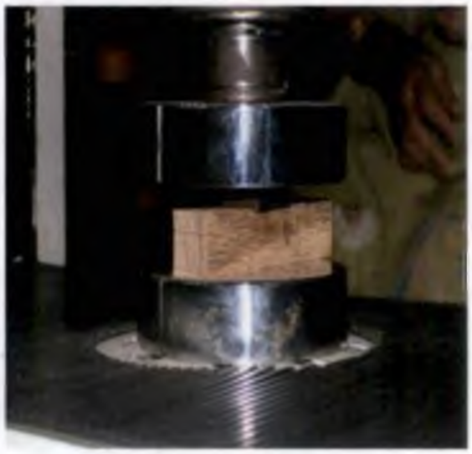


Plate 29. Test for compression strength perpendicular to grain

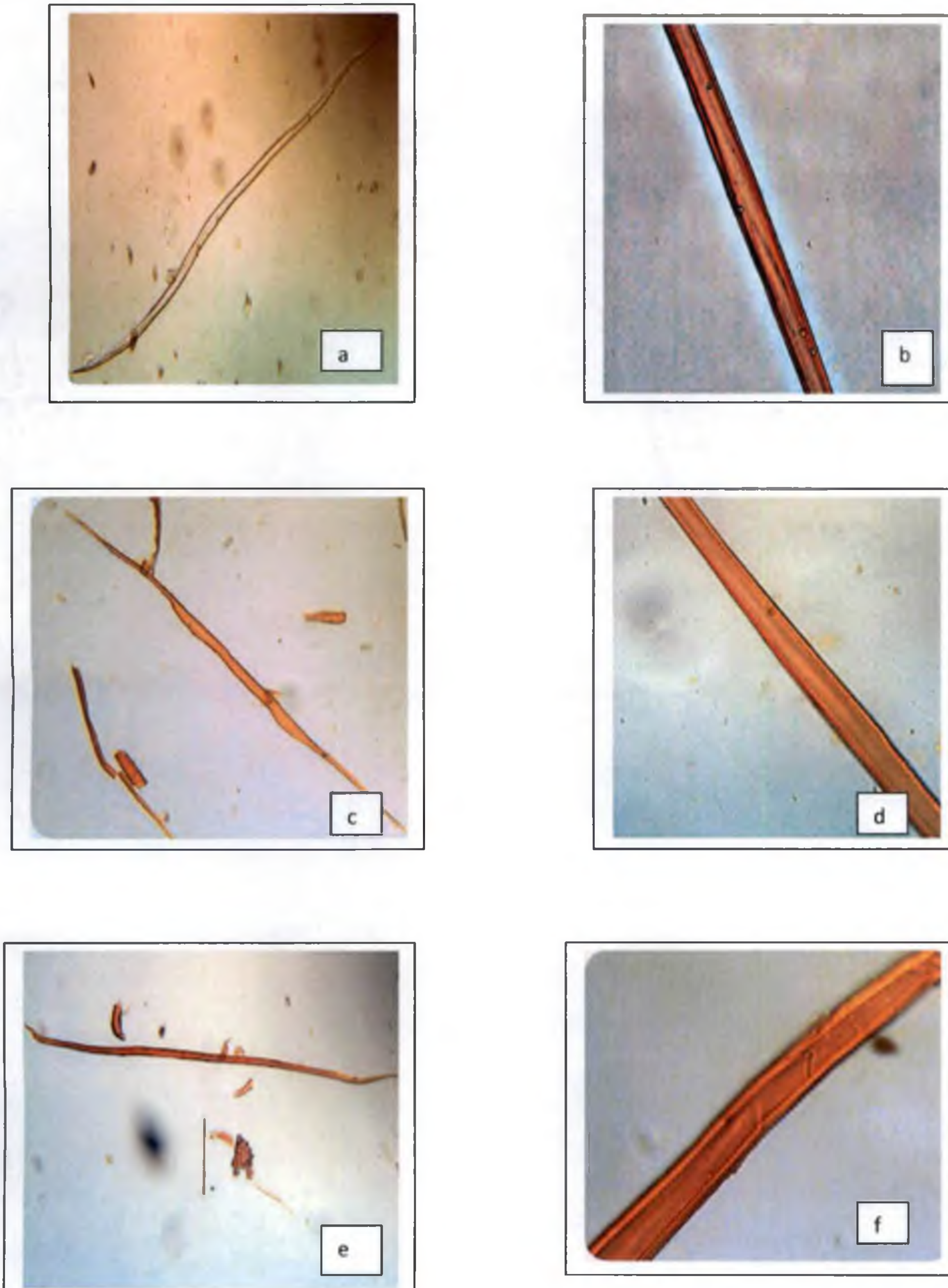


Plate 30. (a)Macerated fibre *of Swietenia macrophylla* (4x); (b) at (10x)
(c) Macerated fibre of *Pterocarpus dalbergioides* (4x); (d) at (10x)
(e) Macerated fibre of *Pericopsis mooniana* (4x); (f) at (10x)

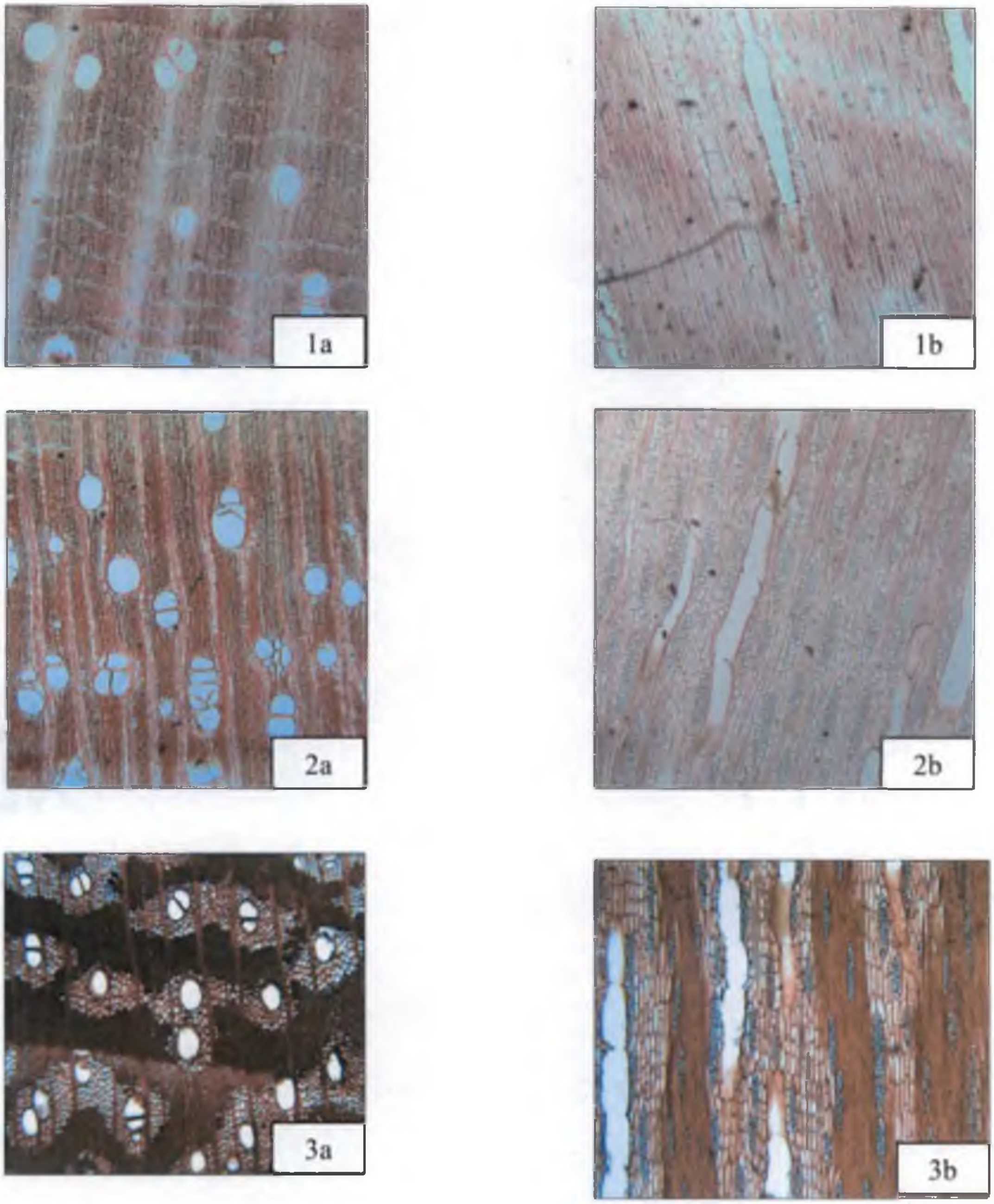


Plate 31. *Pterocarpus dalbergioides:* (1a) Transverse section (4x), (1b) tangential longitudinal section (4x);, *Swietenia macrophylla:* (2a) Transverse section (4x and (2b) tangential longitudinal section (4x); *Pericopsis mooniana* (3a) Transverse section (4x), (3b) tangential longitudinal section (4x)

deflection and stress, and plots the load x deflection curve on the monitor simultaneously with the test. Before the start of a test, the instrument is calibrated for type of test, rate of loading dimensions of samples as per IS 1708: 1986 (ISI, 1986). On the completion of the test the stress x strain graph can be directly read from the monitor and various parameters corresponding to the test can be recorded.

3.5.2 Preparation of test samples

Scantling of size 5 cm x 5 cm cross section and 1.2 m in length were cut out from logs in green condition. These scantling were converted in to standard small clear specimens for different tests as per IS 2488: 1990 specified by ISI (1990). Part of the samples was air-dried to moisture content of 12-20 percent. The samples were transferred to a conditioning chamber to condition all the samples to a moisture percent of 12 ± 2 percent. All the mechanical tests were done at green as well as air dry condition.

3.5.3 Testing of samples

3.5.3.1 Static bending tests

Samples of size 2 cm x 2 cm cross section and 30 cm in length were tested as per IS1708 (Part5): 1986 (ISI, 1986). Before loading the samples for testing, the width and thickness were accurately measured. The samples were loaded such that the stress is on the tangential plane. The machine was calibrated to set the deflection and load at zero and the rate of loading was set at 1mm/minute. The load x deflection curve was read from the monitor. The parameters viz., modulus of elasticity (MOE), modulus of rupture (MOR), maximum load (ML), fiber stress at limit of proportionality (FS at LP), horizontal shear stress at limit of proportionality (HS at LP) and horizontal shear stress at maximum load (HS at ML) were recorded for further reanalysis.

Reanalysis of the derived data was done to calculate MOE accurately. The software calculates MOE over a range of deflection at limit of proportionality. To overcome this discrepancy, the tangent of the curve was adjusted to the maximum and deflection corresponding to the proportionality limit was recorded. By substituting the value thus attained in the following formulae, various parameters were reanalysed.

a) Fiber stress at limit of proportionality (kg/cm^2) (FS at LP) = $3\ Pl/2bh^2$

b) Modulus of rupture (kg/cm^2) (MOR) = $3P'l/2bh^2$

c) Modulus of elasticity (kg/cm^2) (MOE) = $Pl^3/4\Delta BH^3$

d) Horizontal shear stress on neutral plane at limit of proportionality (kg/cm^2) (HS at LP)= $3P/4bh$

e) Horizontal shear stress at maximum load (kg/cm^2) (HS at ML) = $3P'/4bh$

f) Maximum Load (kg) (ML) = CA''/lbh

P = Load in kg at the limit of proportionality which shall be taken as the point in load deflection curve above which the graph deviates from the straight line

l = Span of the test specimen in cm

b = Breadth of test specimen in cm

P' = Maximum load in kg

Δ = Deflection in cm at the limit of proportionality

C = Area constant in kg.cm (the energy represented by one square centimeter which is equal to load in kg, represented by one square centimeter ordinate multiplied by deflection in centimeters, represented by one centimeter abscissa).

A = Area in cm^2 of load deflection curve up to limit of proportionality

The testing of samples is illustrated in plate 27.

3.5.3.2 Compression strength parallel to grain

Samples of cross section 2cm x 2 cm and eight centimetre in length (Fig. 1b) were tested as per IS 1708 (Part 8): 1986 (ISI, 1986). Before test, the width, thickness and length of the samples were recorded. The rate of loading was calibrated to 0.6 mm/min and the load and deflection was set to zero. The sample was loaded with its longitudinal axis along the direction of movement of head. The machine was stopped when the deflection reached 2.5

mm. Various parameters were recorded from the monitor and MOE reanalysed by the formulae is given below.

a) Compressive stress at limit of proportionality (kg/cm2) (CS at LP) = P/A
b) Compressive stress at maximum load (kg/cm2) (CS at ML) = P'/A
c) Modulus of elasticity in compression parallel to grain (kg/cm2) = LP/ΔA

Where,

P = Load at limit of proportionately in kg

A = Cross sectional area of specimen in cm^2

P' = Maximum crushing load in kg

L = Length of the specimen in cm

Δ = Deformation at the limit of proportionately in cm

The samples being tested are illustrated in Plate 28.

3.5.3.3 Compression strength perpendicular to grain

Samples of 2 cm x 2 cm cross section and 10 cm length were tested as per IS 1708 (Part 9): 1986 (ISI, 1986). The sample was loaded such that the tangential plane faces the stress. The linear dimensions of the samples were recorded before test. Rate of loading was calibrated to 0.6 mm/minute and the deflection and load were set to zero. The machine was stopped at a deflection of 2.5 mm or above. Various parameters were read from the monitor and graph adjusted to reanalyse the MOE. The following parameters were calculated using the formulae.

a) Compressive stress at limit of proportionality (kg/cm2) (CS at LP) = P/A
b) Compressive stress at maximum load (kg/cm2) (CS at ML) = P'/A

c) Modulus of elasticity in compression parallel to grain (kg/cm2) = P/ΔA

Where,

P = Load at limit of proportionately in kg

A = Area of cross section normal to the direction of load or area of metal plate used is 3x2 cm.

P' = Load at 2.5 mm compression in kg

H = Height of the specimen in cm

Δ = Deformation at the limit of proportionately in cm

The testing of samples is illustrated in Plate 29.

3.6 STATISTICAL ANALYSIS

The present study was aimed at exploring the wood variability within trees for different hardwood species viz., *Pterocarpus dalbergioides*, *Swietenia macrophylla* and *Pericopsis mooniana* located in the research trials of Kerala forest department. At each location, few trees for each species were taken as replications and the observations were made at three levels viz., pith, middle and periphery within the tree, at breast height level for studying the horizontal variation of wood properties within the trees for studying variation in anatomical properties. Thus sampling and sub sampling (between positions) at species level as well as comparison between species makes a nested or hierarchical classification (Sokal and Rohlf, 2000), NESTED ANOVA was carried out to find variation that exist within tree for different species using SAS (ver.10).

One-way analysis of variance, followed by LSD was use to find out the variation in bark thickness, heartwood percentage, sawn wood recovery rate, and various mechanical properties between tree species. After analysis, significant data pertaining to different wood properties were used to examine the correlation between different wood properties. Regression analysis was carried out to find out the relationship between selected wood variables, finally the best suited model were selected based on adjusted R^2 (Coefficient of determination).

Results

RESULTS

The results pertaining to variation in physical, anatomical and mechanical properties of the three selected tree species viz., Andaman padauk (*Pterocarpus dalbergioides* L.f), big leaf mahogany (*Swietenia macrophylla* Roxb.) and nedun tree (*Pericopsis mooniana* (Thwaites) Thwaites), grown in the research trials of the Kerala forest department at various localities are furnished below under the following categories.

4.1 PHYSICAL PROPERTIES

4.1.1 Moisture content

4.1.1.1a Variation in moisture content (green to oven dry) between species and between radial positions within species

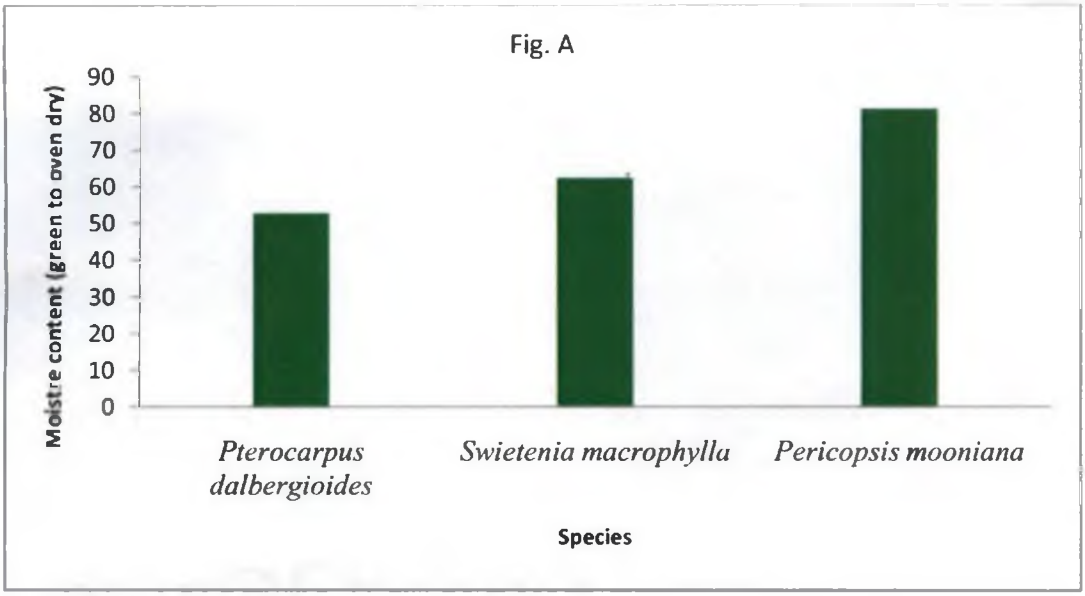
Variation in moisture content (green to oven dry) in *Pterocarpus dalbergioides, Swietenia macrophylla* and *Pericopsis mooniana as* well as radial variation within species (figure 3 and 4) are illustrated in table 3.

Table 3. Variation in moisture content (green to oven dry) between species and between radial positions

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	58.09 (5.69)	55.02 (9.00)	68.79 (22.63)
Middle	48.54 (12.33)	57.56 (12.12)	97.92 (39.42)
Periphery	51.67 (9.93)	74.51 (13.80)	76.42 (28.26)
CD for comparing position	32.33	32.33	41.73
Species average	52.76^{B}	62.36^{AB}	81.04^{A}
CD value for comparing between species 1 and 2 =18.66			
CD value for comparing between species 3 with 1 and 2 =21.55			

Note: Means with the same superscripts between species are homogeneous

Species variation in moisture content (green to oven dry) between *Pterocarpus dalbergioides, Swietenia macrophylla* and *Pericopsis mooniana* showed significant difference at one percent level. *P. dalbergioides* (52.76) and *P. mooniana* (81.04) differed



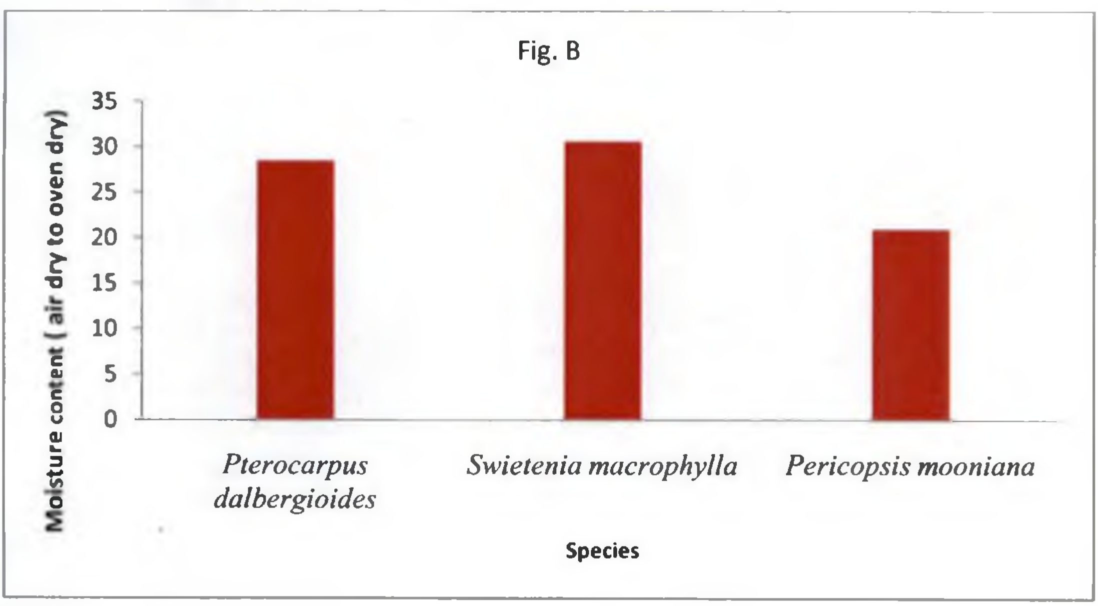
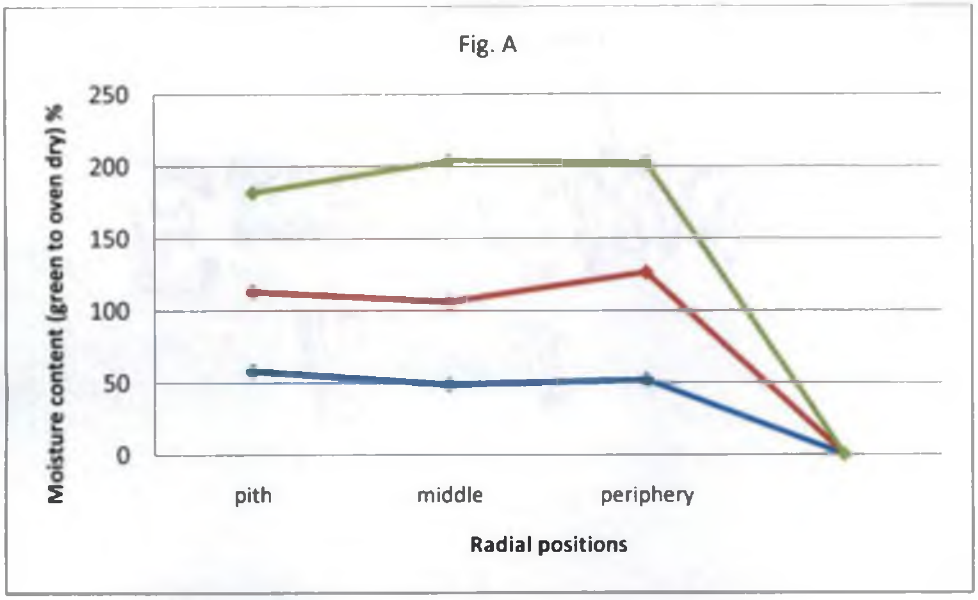


Fig 3. Variation in moisture content between species: (A) Green to oven dry; (B) Air dry to oven dry



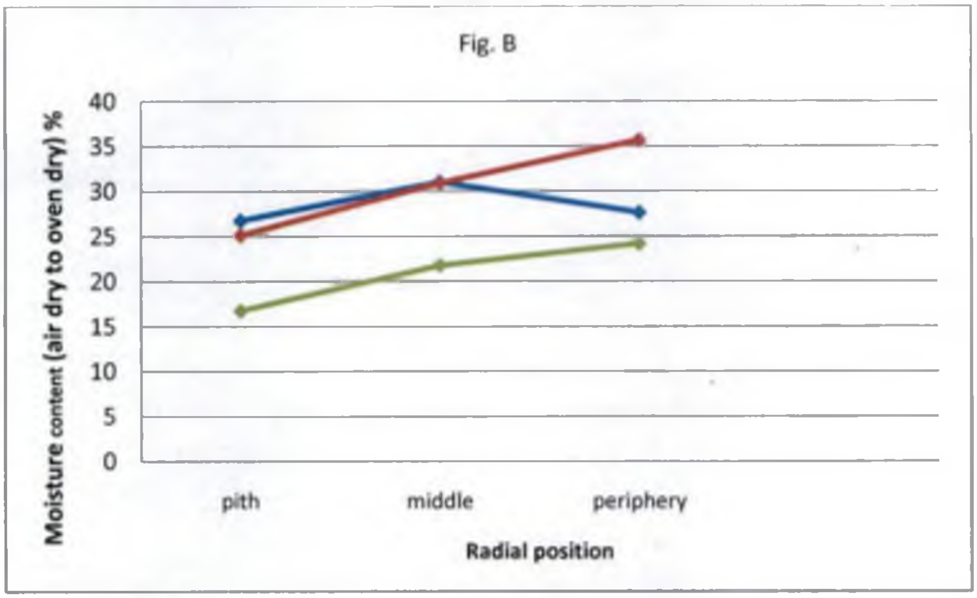


Fig 4. Radial variation in moisture content within species: (A) Green to oven dry (B) Air dry to Oven dry

Pericopsismooniana —◆— *Swieteniamacrophylla* —◆— *Pterocarpusdalbergioides* —◆—

significantly each other whereas both of them were found to be homogeneous to *S. macrophylla* (62.36) with regard to the moisture content value (green to oven dry).

Radial variation in moisture content (green to oven dry) within species was found to be non significant. *P. dalbergioides* had values that ranged from 48.54 (middle) to 58.09 (pith). Value showed a decreasing trend from pith towards middle and then found to be increased towards periphery (51.67). *S. macrophylla* showed an incresing trend towards periphery (74.51) from the pith (55.02). *P. mooniana* showed an increasing trend from pith (68.79) to middle (97.92) and then a decreasing trend towards periphery (76.42).

4.1.1.1b Variation in moisture content (air dry to oven dry) between species and between radial positions within species

Variation in moisture content (air dry to oven dry) between species and radial variation within species are presented in table 4.

Table 4. Variation in moisture content (air dry to oven dry) between species and between radial positions

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	26.72 (4.41)	25.10 (8.02)	16.74 (2.29)
Middle	30.99 (13.51)	30.88 (11.88)	21.77 (14.09)
Periphery	27.60 (3.69)	35.64 (15.18)	24.17 (13.55)
CD for comparing position	18.58	18.58	23.99
Species average	28.44	30.54	20.89
CD value for comparing between species 1 and 2 =10.73 CD value for comparing between species 3 with 1 and 2 =12.39			

Analysis revealed that variation between species as well as radial variation within trees among all species was found to be non significant (figure 3 and 4). Species average with regard to moisture content (air dry to oven dry) was 30.54 % in *S. macrophylla,* 28.44 % for *P. dalbergioides and* 20.89 % in *P. mooniana.*

Radial variation in moisture content (air dry to oven dry) in *P.dalbergioides* showed an increasing trend towards middle position (30.99) from pith (26.72) and then found to be decreased towards periphery (27.60). *S. macrophylla* was found to have increasing moisture content values from pith (25.10) towards periphery (35.64). Similarly *P. mooniana* was also found to have an increasing trend in moisture content (air dry to oven dry) towards periphery (24.77) from pith (16.74).

4.1.2 Specific gravity

4.1.2.1 Specific gravity (fresh weight basis)

4.1.2.1a Variation in specific gravity (fresh weight) between species and between radial positions within species

Analysis of variance conducted revealed that specific gravity (fresh weight) differed significantly at one percent level between species (figure 5 and 6). Results are presented in table 5. *P. mooniana* (1.20) accounted for the highest significant species average for green specific gravity followed by *S. macrophylla* (1.03) and *P. dalbergioides* (0.77).

Table 5. Variation in specific gravity (fresh weight) between species and between radial positions

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	0.62 (0.06)	1.00 (0.14)	1.19 (0.05)
Middle	0.84 (0.11)	1.04 (0.25)	1.16 (0.03)
Periphery	0.86 (0.04)	1.4 (0.19)	1.24 (0.10)
CD for comparing position	0.25	0.25	0.32
Species average	0.77^{C}	1.03^{B}	1.20^{A}
CD value for comparing between species 1 and 2 =0.14 CD value for comparing between species 3 with 1 and 2 =0.16			

Note: Means with the superscripts between species are homogeneous

From table 5 it can be seen that variation between positions within species was found to be non significant. *P. dalbergioides* had values that ranged from 0.62 (pith) to 0.86

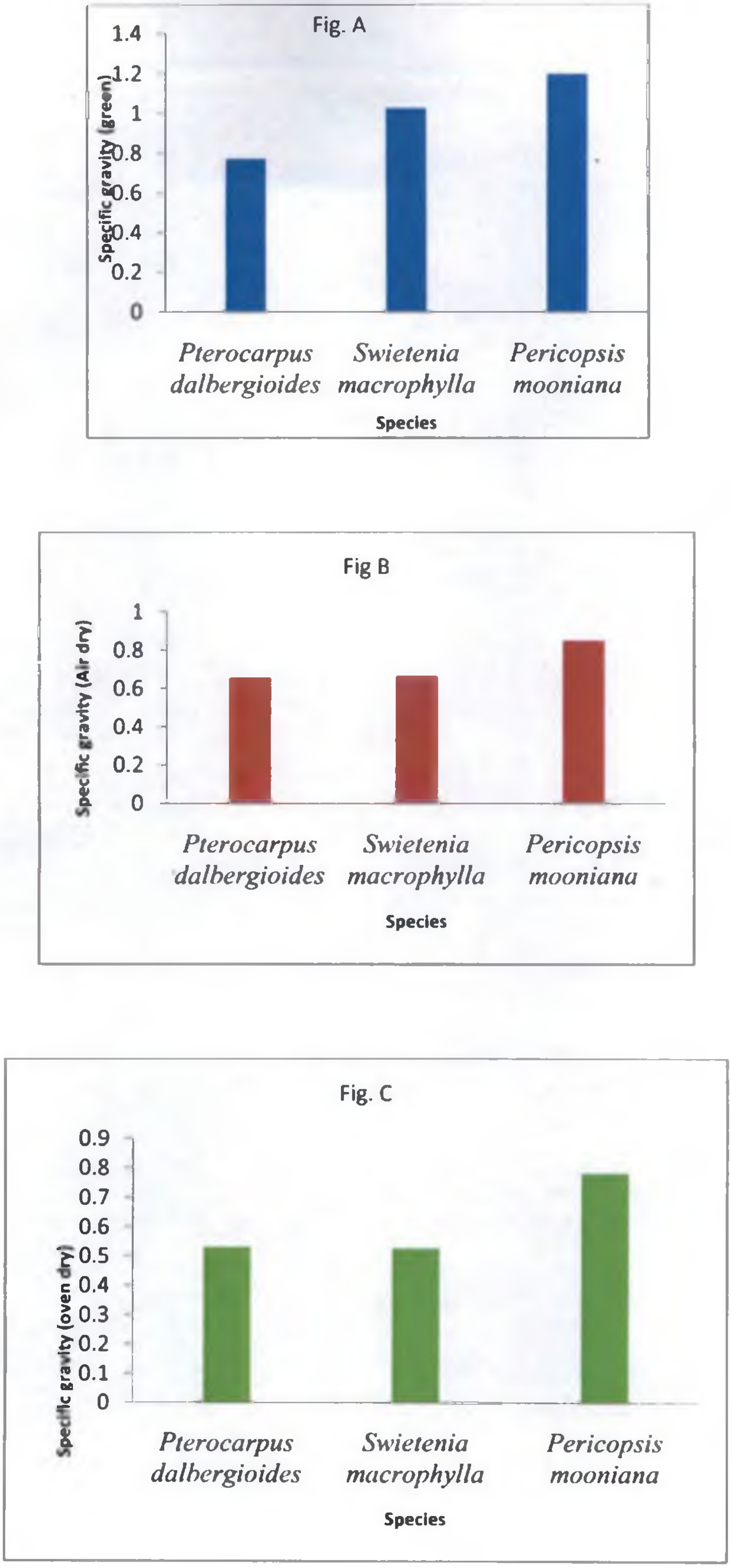


Fig 5. Variation in specific gravity between species: (A) Green condition (B) Air dry condition (C) Oven dry condition

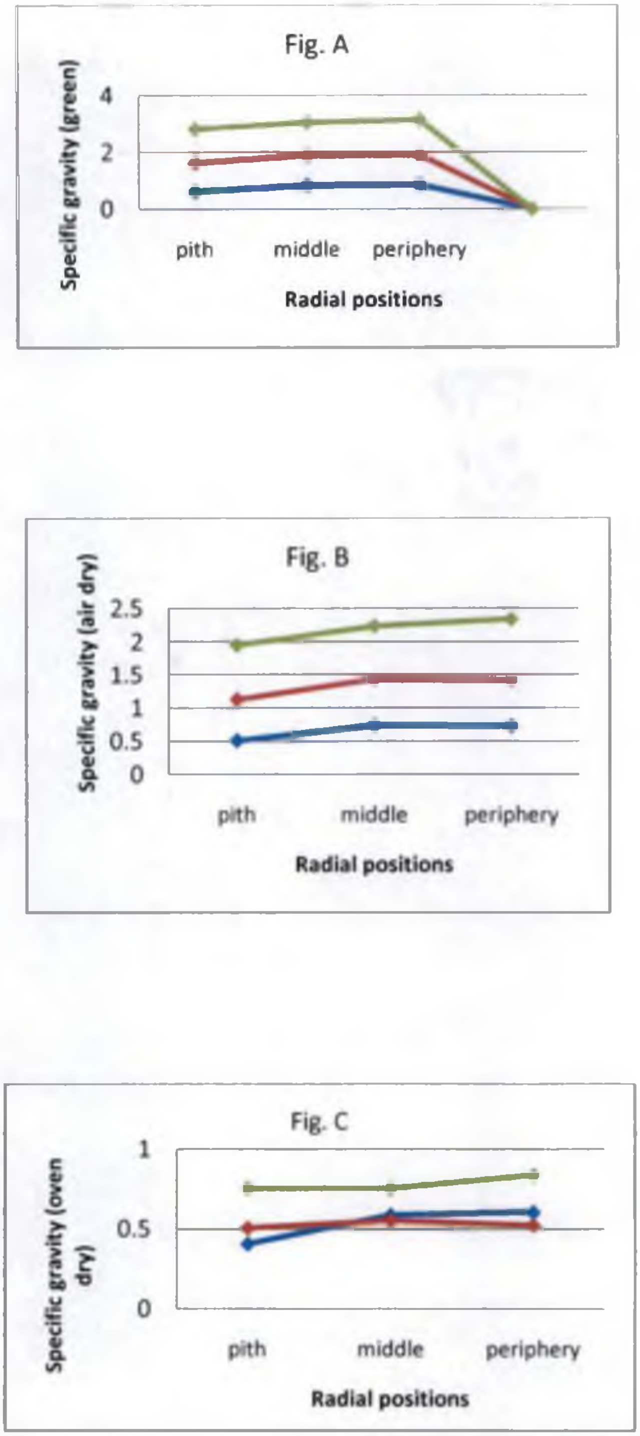


Fig 6. Radial variation in specific gravity: (A) Green condition; (B) Air dry condition and(C) Oven dry condition within species

Pericopsis mooniana;	*Swietenia macrophylla;*	*Pterocarpus dalbergioides*

(periphery) and an increasing trend in specific gravity was observed from pith towards periphery. In the case of *S. macrophylla* the values ranged from 1.00 (pith) to 1.04 (periphery). *P. mooniana* had values ranging from 1.16 (middle) to 1.24 (periphery). *S. macrophylla* showed an increasing trend towards periphery from pith whereas, *P. mooniana* showed a declining trend from pith towards middle, thereafter showed an increasing trend.

4.1.2.1b Variation in air dry specific gravity between species and between radial positions within species

Table 6 summarises the results of variation in air dry specific gravity between species and between radial positions within species. Analysis of variance revealed that between species difference was significant (at 1% level) among *P. dalbergioides, S. macrophylla and Pericopsis mooniana* (figure 5 and 6). *Pericopsis mooniana* (0.85) showed the highest value for air dry specific gravity and was significantly differed from other two species. *S. macrophylla* (0.67) and *P. dalbergioides* (0.66) were at par with regard to air dry specific gravity.

Table 6. Variation in specific gravity at air dry condition between species and between radial positions within species

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	0.51^{b} (0.06)	0.62^{a} (0.05)	0.83^{a} (0.07)
Middle	0.74^{a} (0.12)	0.69^{a} (0.11)	0.80^{a} (0.08)
Periphery	0.73^{a} (0.06)	0.69^{a} (0.09)	0.92^{a} (0.05)
CD for comparing position	0.17	0.17	0.22
Species average	0.66^{B}	0.67^{B}	0.85^{A}
CD value for comparing between species 1 and 2 =0.10 CD value for comparing between species 3 with 1 and 2 =0.12			

Note: Means with the same superscripts between species are homogeneous
Means with the same superscripts within a species are homogeneous

From table 6 it was evident that significant variation in air dry specific gravity existed along the radial positions among the three species under study. In the case of *P. dalbergioides* pith position (0.51) differed significantly from middle (0.74) and periphery (0.73), whereas the latter two positions were found to be homogeneous with regard to air dry specific gravity.

S. macrophylla showed similar values for pith (0.62), middle (0.69) and periphery (0.69) positions. Similarly *P. mooniana* was also found to have homogeneous values at pith (0.83), middle (0.80) and periphery positions (0.92). *S. macrophylla* and *Pterocarpus dalbergioides* showed an increasing trend in air dry specific gravity from pith towards middle, whereas *P. mooniana* was found to have a decreasing trend towards middle from the pith and thereafter showed an increasing trend towards periphery.

4.1.2.1c Variation in oven dry specific gravity between species and between radial positions within species

Table 7 illustrates the analysis of oven dry specific gravity in different species as well as between radial positions within species (figure 5 and 6).

Table 7. Variation in oven dry specific gravity between species and between radial positions

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	0.41^{b} (0.047)	0.51^{a} (0.019)	0.75^{a} (0.090)
Middle	0.59^{a} (0.034)	0.55^{a} (0.068)	0.75^{a} (0.077)
Periphery	0.60^{a} (0.072)	0.52^{a} (0.041)	0.84^{a} (0.088)
CD for comparing position	0.11	0.11	0.14
Species average	0.53^{B}	0.53^{B}	0.78^{A}
CD value for comparing between species 1 and 2 =0.06			
CD value for comparing between species 3 with 1 and 2 =0.07			

Note: Means with the same superscripts within a species are homogeneous
Means with the same superscripts between species are homogeneous

Results revealed that between species difference was significant (at 1% level) among *P. dalbergioides, S. macrophylla and Pericopsis mooniana. Pericopsis mooniana* (0.78) showed the highest value for oven dry specific gravity and was significantly differed from the other two species. *S. macrophylla* (0.53) and *P. dalbergioides* (0.53) showed homogeneous values with respect to oven dry specific gravity.

From table 7 it can be seen that significant variation (at 1% level) in oven dry specific gravity existed along the radial positions among the three species under study. In the case of *P. dalbergioides* pith position (0.41) differed significantly from middle (0.59) and periphery (0.60), whereas the latter two positions were found to be similar with regard to oven dry specific gravity. *S. macrophylla* showed homogeneous values for pith (0.51), middle (0.55) and periphery (0.52) positions. Similarly *P. mooniana* was found to have similar values at pith (0.75), middle (0.75) and periphery positions (0.84).

4.1.3 Shrinkage

4.1.3.1 Radial shrinkage

4.1.3.1a Variation in radial shrinkage (green to air dry) between species and between radial positions within species

Result of analysis of variance (table 8) revealed that between species variation among the three species studied were found to be significant at one percent level whereas, radial variation within trees in each species did not show any significant difference with respect to radial shrinkage (green to air dry).

Species averages were found to be higher in *P. mooniana* (2.16), followed by *P. dalbergioides* (0.74) and *S. macrophylla* (0.49). With regard to radial variation, *P. dalbergioides* showed a decreasing trend from pith (1.04) towards periphery (0.51), whereas *S. macrophylla* showed an increasing trend towards middle from the pith region and thereafter found to be decreased towards periphery. *S. macrophylla* had values that ranged from 0.42 (pith) to 0.60 (middle). *P. mooniana* first showed decline from pith (2.18) towards middle (2.12) then showed an increasing trend towards periphery (2.18) (figure 7 and 8).

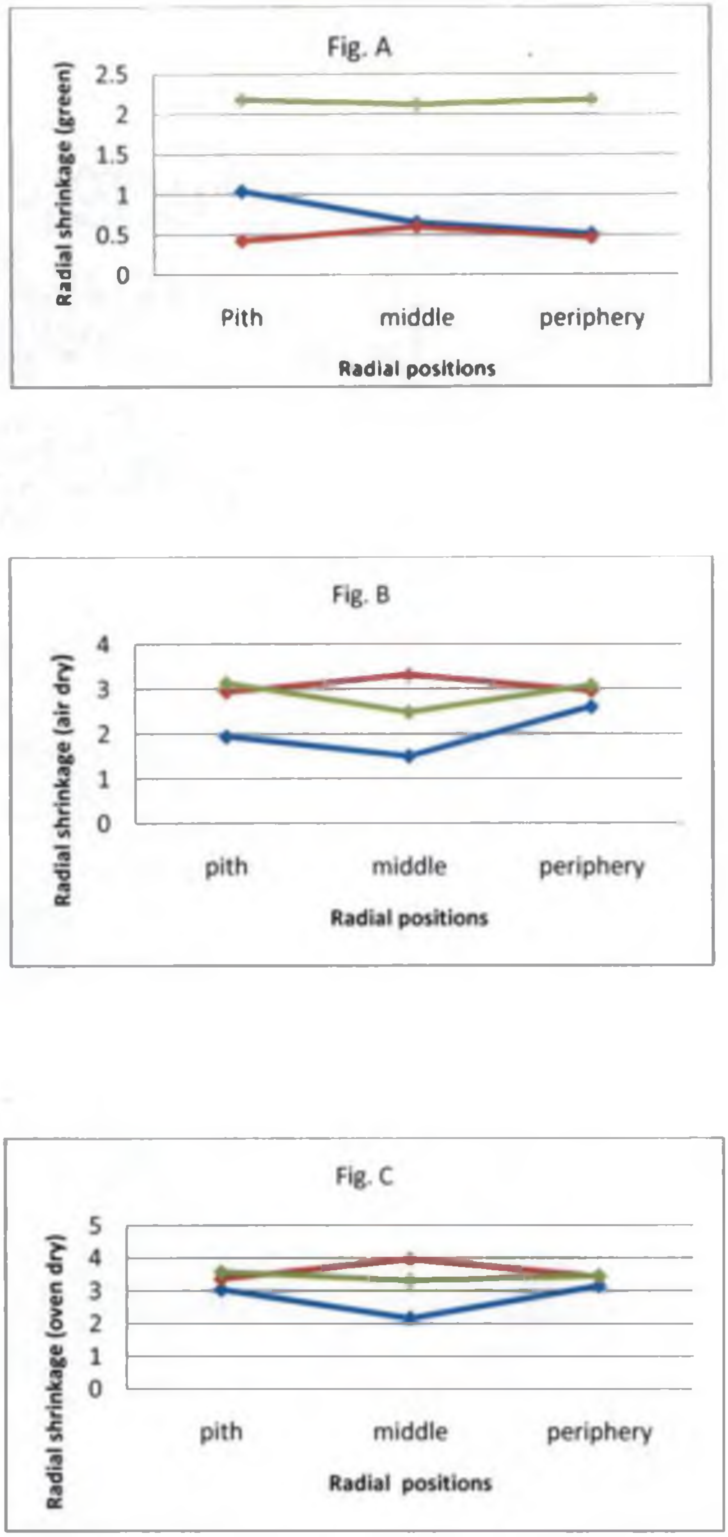
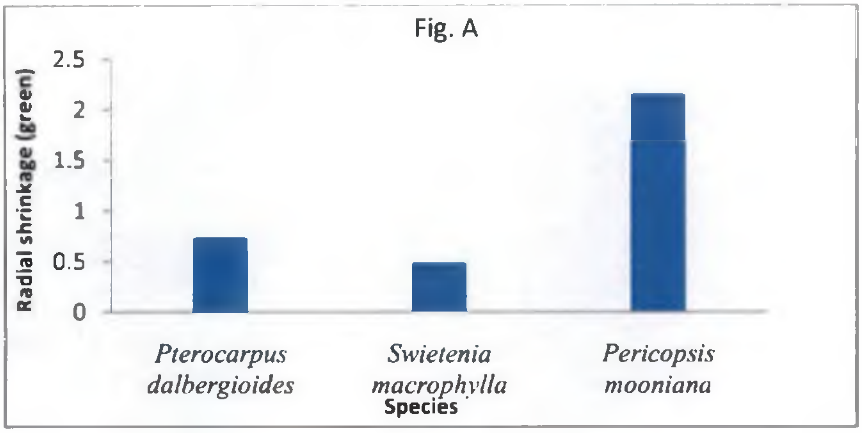
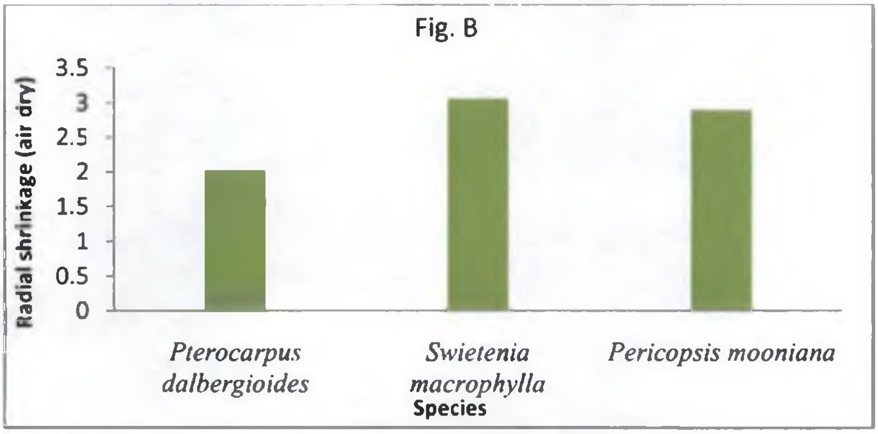


Fig 7: Radial variation in radial shrinkage within species: (A) Green condition; (B) Air dry condition; (C) Oven dry condition

Pericopsis mooniana ; *Swietenia macrophylla* ; *Pterocarpus dalbergioides*





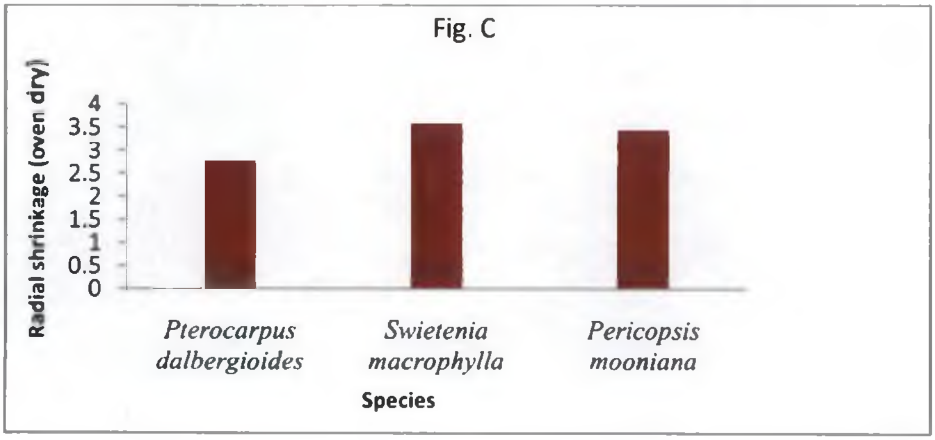


Fig 8. Variation in radial shrinkage: (A) Green condition; (B) Air dry condition; (C) Oven dry condition between species

Table 8. Variation in radial shrinkage (green to air dry) (%) between species and between radial positions

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	1.04 (0.85)	0.42 (0.16)	2.18 (0.16)
Middle	0.65 (0.25)	0.60 (0.62)	2.12 (0.16)
Periphery	0.51 (0.20)	0.46 (0.11)	2.18 (0.11)
CD for comparing position	0.87	0.87	0.93
Species average	0.74^{B}	0.49^{B}	2.16^{A}
CD value for comparing between species 1 and 2 = 0.50 CD value for comparing between species 3 with 1 and 2 = 0.58			

Means with the same superscripts between species are homogeneous

4.1.3.1b Variation in radial shrinkage (air dry to oven dry) (%) between species and between radial positions within species

Between tree variations as well as within tree radial variation among *P. dalbergioides*, *S. macrophylla* and *P .mooniana* with regard to radial shrinkage (air dry to oven dry) are presented in table 9. It can be seen that between variation between species differed significantly (1%) among the three species under study. *S. macrophylla* (3.06) was found to have the highest value for radial shrinkage (air dry to oven dry) followed by *P. mooniana* (2.89) and *P. dalbergioides* (2.02). *P. mooniana* and *S. macrophylla* were at par (figure 7 and 8).

From Table 9 it was noticed that within tree radial variation with regard to radial shrinkage (air dry to oven dry) among species under study was found to be non-significant. *P. dalbergioides* had values that ranged from 1.50 (middle) to 2.60 (periphery).

Table 9. Variation in radial shrinkage (air dry to oven dry) (%) between species and between radial positions

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	1.94 (0.70)	2.93 (0.43)	3.13 (0.03)
Middle	1.50 (0.48)	3.31 (0.21)	2.48 (0.12)
Periphery	2.60 (0.78)	2.95 (0.32)	3.07 (0.01)
CD for comparing position	1.71	1.71	1.05
Species average	2.02^{B}	3.06^{A}	2.89^{A}
CD value for comparing between species 1 and 2 = 0.99 CD value for comparing between species 3 with 1 and 2 = 1.14			

Note: Means with the same superscripts between species are homogeneous

It showed a decreasing trend from pith towards middle then found to be increased towards periphery position. *S. macrophylla* showed a reverse trend of increasing radial shrinkage values from pith (2.93) towards middle (3.31) and a decreasing trend towards periphery (2.95) position. *P. mooniana* showed a decreasing trend in radial shrinkage from pith (3.13) to middle (2.48) and thereafter it showed a slight increase towards periphery (3.07).

4.1.3.1c Variation in radial shrinkage (green to oven dry) between species and between radial positions within species

Results of analysis of variance (table 10) revealed that between tree variation among different species as well as within species variation differed significantly at one percent level and five percent level respectively (figure 7 and 8) with regard to the radial shrinkage (green to oven dry). *S. macrophylla* (3.58) showed the highest species average for radial shrinkage (green to oven dry), followed by *P. mooniana* (3.44) and *P. dalbergioides* (2.78). *P. mooniana* and *S. macrophylla* were at par.

Table 10. Variation in radial shrinkage (green to oven dry) between species and between radial positions

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	3.03^{a} (0.36)	3.36^{a} (0.52)	3.57^{a} (0.09)
Middle	2.16^{b} (0.41)	3.95^{a} (0.53)	3.31^{a} (0.23)
Periphery	3.14^{a} (0.75)	3.42^{a} (0.53)	3.45^{a} (0.10)
CD for comparing position	1.64	1.64	1.03
Species average	2.78^{B}	3.58^{A}	3.44^{A}
CD value for comparing between species 1 and 2 = 0.95 CD value for comparing between species 3 with 1 and 2 = 1.09			

Note: Means with same superscripts within a species are homogeneous
Means with the same superscripts between species are homogeneous

Regarding the radial variation within species, there was a decreasing trend from pith (3.03) to middle (2.16) thereafter found to increased towards periphery (3.14) in the case of *P. dalbergioides* whereas *S. macrophylla* showed a reverse trend of increasing radial shrinkage values (green to oven dry) from pith (3.36) towards middle (3.95) and thereafter declined towards periphery (3.42). *P. mooniana* had values that ranged from 3.31 (middle) to 3.57 (pith).

4.1.3.2 Tangential shrinkage

4.1.3.2a Variation in tangential shrinkage (green to air dry) between species and between radial positions within species

Analysis of result pertaining to tangential shrinkage (green to air dry) revealed that significant (1% level) difference existed between species, whereas radial variation within trees for each (table 11) species was found to be non significant (figure 9 and 10). Between species comparison revealed that *S. macrophylla* (4.55) had maximum tangential shrinkage (green to air dry) followed by *P. mooniana* (4.15) and *P. dalbergioides* (0.92).

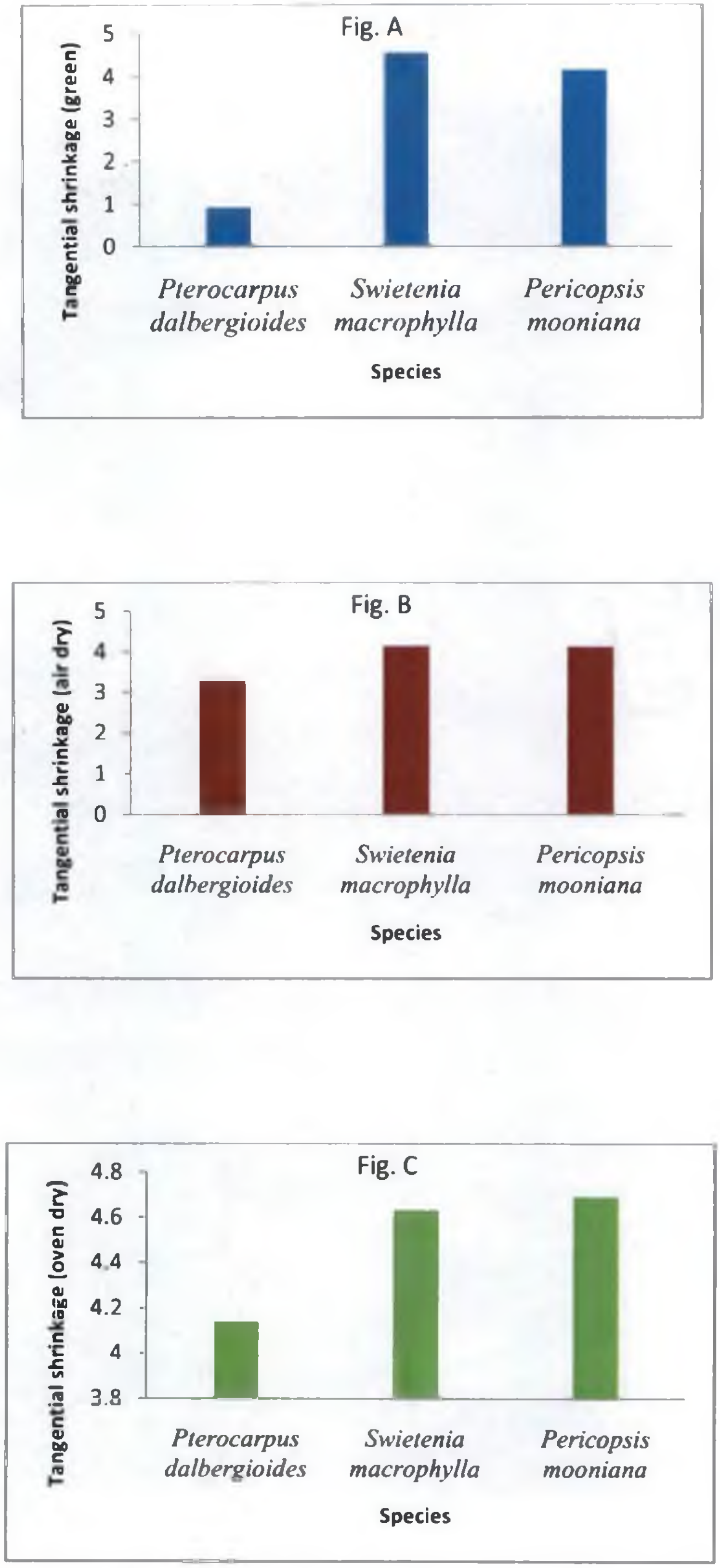


Fig 9: Variation in tangential shrinkage between species: (A) Green condition; (B) Air dry condition; (C) Oven dry condition

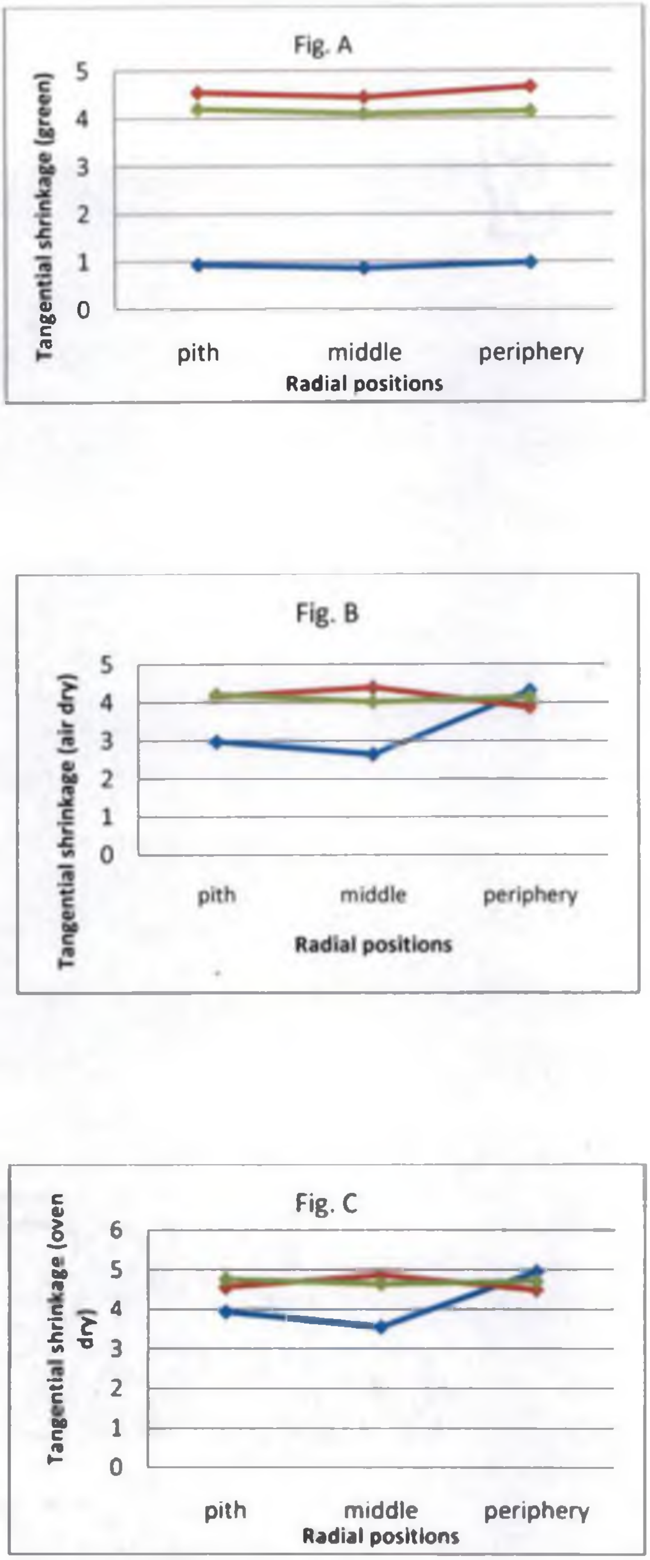


Fig 10. Radial variation in tangential shrinkage within species: (A) Green condition; (B) Air dry condition; (C) Oven dry condition

Pericopsis mooniana ;	*Swietenia macrophylla* ;	*Pterocarpus dalbergioides*

Table11. Variation in tangential shrinkage (green to air dry) between species and between radial positions

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	0.93 (0.29)	4.54 (0.30)	4.20 (0.26)
Middle	0.86 (0.45)	4.44 (0.23)	4.10 (0.19)
Periphery	0.97 (0.48)	4.66 (0.43)	4.15 (0.25)
CD for comparing position	0.78	0.78	0.78
Species average	0.92^{C}	4.55^{A}	4.15^{A}
CD value for comparing between species 1 and 2 = 0.45 CD value for comparing between species 3 with 1 and 2 = 0.52			

Note: Means with the superscripts between species are homogeneous

Radial variation in tangential shrinkage (green to air dry) in *P. dalbergioides* showed decreasing trend from the pith (0.93) towards the middle (0.86) position thereafter found to be increased towards periphery (0.97). Similarly *S. macrophylla* showed the same pattern of reduction in tangential shrinkage (green to air dry) from pith (4.54) towards middle (4.44) and thereafter increased towards periphery (4.66). *P. mooniana* showed a decreasing trend from pith (4.20) towards middle (4.10), thereafter found to be increased towards periphery (4.15 %).

4.1.3.2b Variation in tangential shrinkage (air dry to oven dry) between species and between radial positions within species

Table 12 summarises the analysis results of tangential shrinkage (air dry to oven dry) in *P. dalbergioides*, *S. macrophylla* and *P. mooniana*. Results revealed that between species variation as well as within tree radial variation among three species under study were significant at one percent level (figure 9 and 10).

P. dalbergioides (3.31) showed the lowest value with respect to tangential shrinkage (air dry to oven dry). *P. mooniana* (4.12) and *S. macrophylla* (4.14) were found to have similar values for shrinkage (air dry to oven dry).

Table 12. Variation in tangential shrinkage (air dry to oven dry) between species and between radial positions

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	2.97^{ab} (0.75)	4.15^{a} (0.76)	4.21^{a} (0.06)
Middle	2.64^{b} (0.77)	4.39^{a} (0.51)	4.01^{c} (0.16)
Periphery	4.31^{a} (0.68)	3.87^{a} (0.54)	4.14^{b} (0.05)
CD for comparing position	1.06	1.06	1.37
Species average	3.31^{B}	4.14^{A}	4.12^{A}
CD value for comparing between species 1 and 2 = 0.61 CD value for comparing between species 3 with 1 and 2 = 0.71			

Note: Means with same superscripts within a species are homogeneous
Means with same superscripts between species are homogeneous

Within tree variation among *P. mooniana*, *S. macrophylla* and *P. dalbergioides* were found to be significantly differed at one percent level. In the case of *P. dalbergioides*, periphery (4.31) and middle (2.64) position showed significant difference from the pith position (2.97) with regard to tangential shrinkage (air dry to oven dry), moreover periphery position showed the highest value in *P. dalbergioides*. *S. macrophylla* showed homogeneous values for pith (4.15), middle (4.39) and periphery (3.87) positions. *P. mooniana* differed significantly among pith (4.21), middle (4.01) and periphery positions (4.14). Value was higher at the pith, followed by periphery and middle position with regard to the tangential shrinkage (air dry to oven dry).

4.1.3.2c Variation in tangential shrinkage (green to oven dry) between species and between radial positions within species

Analysis results showing variation between species and radial variation with in trees with respect to the tangential shrinkage (green to oven dry) are presented in table13 (figure 9 and 10).

Table 13. Variation in tangential shrinkage green to oven dry between species and between radial positions

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
	Mean	Mean	Mean
Pith	3.93^{b} (0.86)	4.55^{a} (0.94)	4.75^{a} (0.14)
Middle	3.54^{b} (0.41)	4.85^{a} (0.57)	4.63^{a} (0.07)
Periphery	4.94^{a} (0.33)	4.48^{a} (0.33)	4.70^{a} (0.12)
CD for comparing position	0.76	0.76	0.98
Species average	4.14^{B}	4.63^{A}	4.69^{A}
CD value for comparing between species 1 and 2 = 0.44 CD value for comparing between species 3 with 1 and 2 = 0.50			

Note: Means with same superscripts within a species are homogeneous
Means with same superscripts between species are homogeneous

Variations in tangential shrinkage between species as well as radial variation within species were found to be significant at one percent and five percent level respectively. *P. mooniana* (4.69) had the highest value for tangential shrinkage (green to oven dry) followed by *S. macrophylla* (4.63) and *P. dalbergioides* (4.14). *P. mooniana* and *S. macrophylla* were at par with regard to tangential shrinkage (green to oven dry).

In the case of P. *dalbergioides* there was a decreasing trend in tangential shrinkage from pith towards middle thereafter found to be increased towards periphery. *S. macrophylla* had values that ranged from 4.48 (periphery) to 4.85 (middle) position. There was a decreasing trend from pith (4.75) towards the middle region thereafter showed a slight increase towards periphery (4.70) in the case of *P. mooniana*.

4.1.4 Heartwood percent

1.4.1 Variation in heartwood percentage between species

One way anova was carried out to study the heartwood percentage for different species viz., P. *dalbergioides*, *S. macrophylla* and *Pericopsis mooniana and* are summarised in Table 14 and Figure11.

Table 14. Variation in heartwood percentage (%) in *P. dalbergioides, S. macrophylla and Pericopsis mooniana*

SI. No	Species	Mean (%)
1	*Pterocarpus dalbergioides*	52.67^{c} (12.85)
2	*Swietenia macrophylla*	89.13^{a} (2.99)
3	*Pericopsis mooniana*	75.24^{b} (18.60)
CD for comparing species 1and 2		21.84
CD for comparing species 1, 2 with 3		25.15

Means column wise comparison
Values with same superscript do not differ significantly between themselves

It can be seen that variation in heartwood percent between species was highly significant at one percent level. *S. macrophylla* (89.13) showed highest significant value for heartwood percent compared to other two species. It was followed by *P. mooniana* (75.24) and *P. dalbergioides* (52.67).

4.1.4 Bark thickness

4.1.4.1 Variation in bark thickness between species

Table 15 summarises the analysis results of bark thickness between species. Analysis of bark thickness revealed that between species difference was significant (1%) among *P. dalbergioides, S. macrophylla and Pericopsis mooniana. P. dalbergioides* (6.92) showed highest value for bark thickness and were significantly differed from other two species. *S. macrophylla* (2.99) and *P. mooniana* (2.93) showed homogeneous values with regard to bark thickness (figure11).

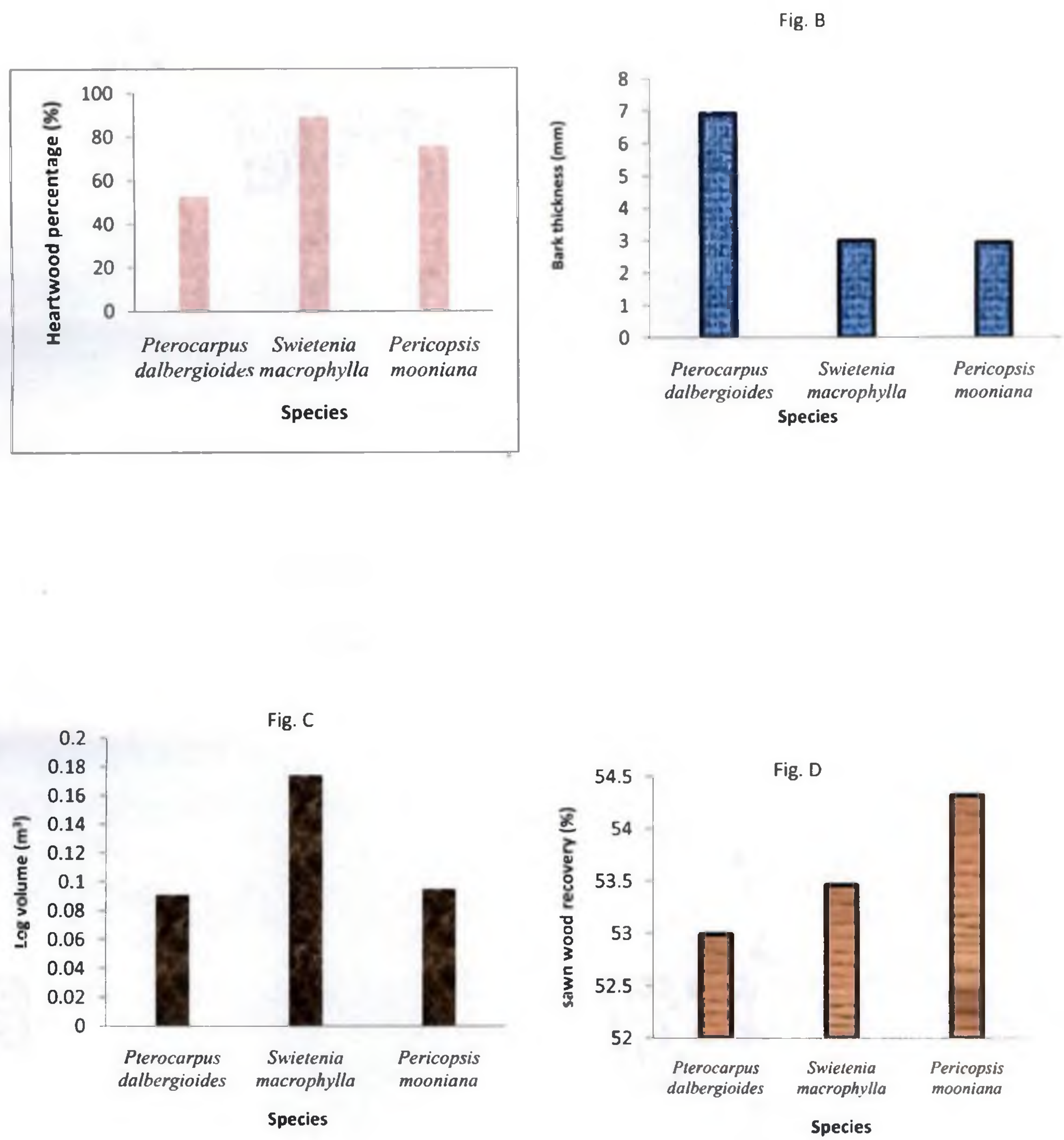


Fig 11. Variation in : (A) Heartwood-sapwood ratio; (B) Bark thickness; (C) Log volume; (D) Sawn wood recovery between species

Table 15. Variation of bark thickness between species in *P. dalbergioides, S. macrophylla and Pericopsis mooniana*

SI. No	Species	Bark thickness (mm)
1	*Pterocarpus dalbergioides*	6.92^{a} (1.46)
2	*Swietenia macrophylla*	2.99^{b} (2.18)
3	*Pericopsis mooniana*	2.93^{b} (0.10)
CD for comparing species1 and 2		4.11
CD for comparing species1,2 and 3		4.74

Means column wise comparison
Values with same superscript do not differ significantly between themselves

4.1.5 Sawn wood recovery

One way anova conducted in log volume and sawn wood recovery for 1m log from the base of *P. dalbergioides, S. macrophylla and Pericopsis mooniana* are furnished in table 16 and figure 11. From the table it is evident that significant difference (1%) exists in log volume among different species under study, whereas between species difference was found to be non significant with respect to sawn wood recovery.

Table 16. Variation of log volume and sawn wood recovery (%) between species in *P. dalbergioides, S. macrophylla and Pericopsis mooniana*

S. No	Species	Log volume (m^3)	Sawn wood recovery (%)
1	*Pterocarpus dalbergioides*	0.091^{b}	52.99
2	*Swietenia macrophylla*	0.174^{a}	53.46
3	*Pericopsis mooniana*	0.095^{b}	54.32
CD for comparing species1 and 2		0.08	-----
CD for comparing species1,2 and 3		0.09	-------

Means column wise comparison
Values with the same superscript do not differ significantly between themselves

Swietenia macrophylla (0.714) showed highest log volume and was significantly differed from *P. dalbergioides* (0.091) and *P. mooniana* (0.095). Latter two species were found to be homogeneous to each other. Sawn wood recovery rate was 54 percent in *P. mooniana*, followed by *S. macrophylla* (53.46) and *P. dalbergioides* (52.99).

4.2 ANATOMICAL PROPERTIES

4.2.1 Vessel morphology

4.2.1.1 Vessel area

4.2.1.1.1 Variation in vessel area between species as well as between positions within species

Variations in vessel area between species as well as between radial positions within species were significant (at 1% level). Between species comparison showed that highest species average in vessel area was found in *Pterocarpus dalbergioides* (58444.2), followed by *Swietenia macrophylla* (33076.7) and *Pericopsis mooniana* (21664.3). Radial variations in vessel area within each species as well as between species are illustrated in Figure 12 and 13.

Table 17. Variation in vessel area (μm^2) between species and between radial positions within species

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	38702.7^{c} (5985.6)	22500.6^{b} (1864.4)	16772.2^{b} (9591.1)
Middle	57406.7^{b} (3430.7)	31487.3^{b} (8127.4)	20525.9^{ab} (1929.4)
Periphery	79223.2^{a} (17491.3)	45242.3^{a} (9591.1)	27694.8^{a} (5346.1)
CD for comparing position	11083.96	11083.96	7389.31
Species average	58444.2^{A}	33076.7^{B}	21664.3^{C}
CD value for comparing between species 1 and 2 =6399.33 CD value for comparing between species 3 with 1 and 2 =6640.90			

Note: Means with same superscripts within a species are homogeneous
Means with the same capital letter as superscripts between species are homogeneous

Among the three species studied, periphery position showed the highest variation in vessel area than pith and middle position. Moreover, there was an increasing trend in vessel area from pith to periphery for all the three species. A comparison between species and positions within each species for vessel area are given in table17.

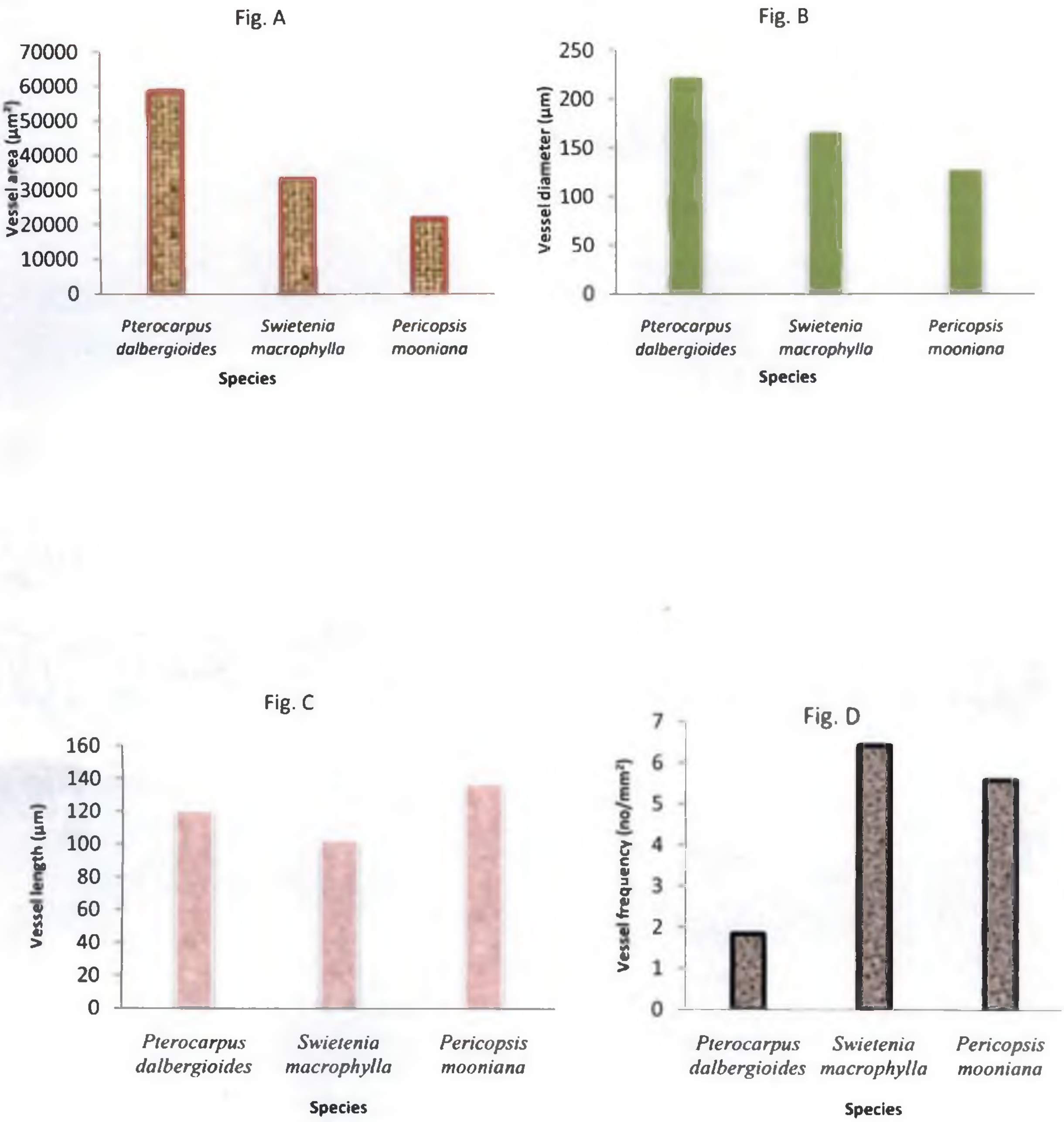


Fig 12. Variation in: (A) Vessel area; (B) Vessel diameter; (C) Vessel length; (D) Vessel frequency between species

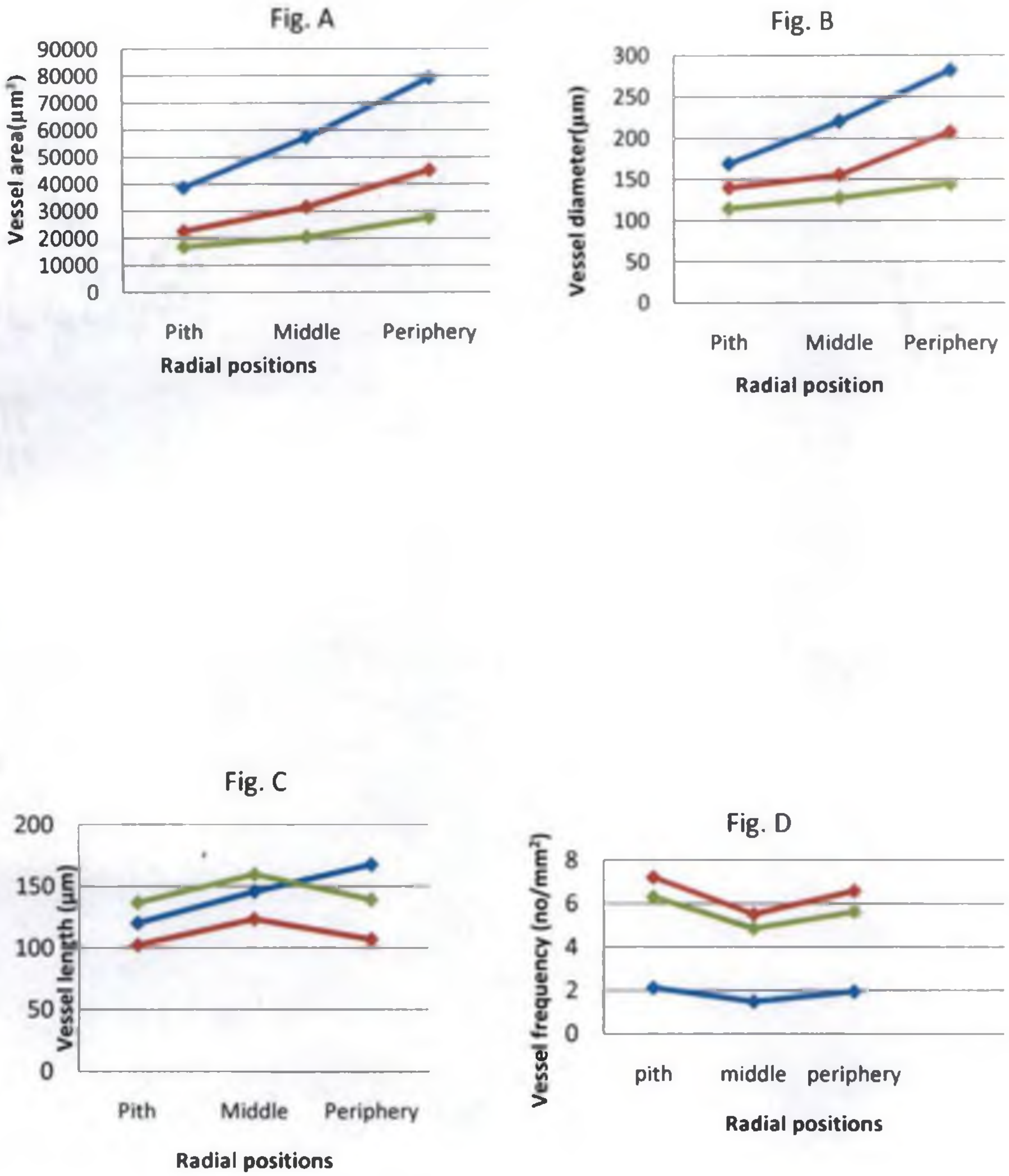


Fig 13. Radial variation within species with regard to (A) Vessel area; (B) Vessel diameter; (C) Vessel length; (D) Vessel frequency

Pericopsis mooniana ;	*Swietenia macrophylla* ;	*Pterocarpus dalbergioides*

From table 17 it can be seen that significant variation of vessel area existed in radial position for *Pterocarpus dalbergioides* with high value in the periphery (79223.2), followed by middle (57406.7) and pith (38702.7) positions. Radial variation in *Swietenia macrophylla* showed a significant difference in periphery (45242.3) compared to the middle (31487.3) and pith (22500.6) values with respect to vessel area. Pith and middle values were found to be homogeneous to each other. In the case of *Pericopsis mooniana* vessel area in the middle position (20525.9) was at par with pith (16772.2) and periphery (27694.8).

4.2.1.2 Vessel diameter

4.2.1.2.1 Variation in vessel diameter between species as well as between positions within species

Radial variation in vessel diameter for *Pterocarpus dalbergioides, Swietenia macrophylla* and *Pericopsis mooniana* are summarised in table 18 (figure 12 and 13). It was noticed from the table that significant difference exists between species and between positions within species with respect to the vessel diameter.

Table 18. Variation in vessel diameter (μm) between species and between radial positions

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	169.0^{c} (7.3)	139.4^{b} (5.3)	114.4^{a} (28.8)
Middle	220.5^{b} (18.8)	155.3^{b} (25.9)	127.3^{a} (15.0)
Periphery	282.3^{a} (36.2)	207.9^{a} (12.3)	144.4^{a} (1.0)
CD for comparing position	26.23	26.23	30.28
Species average	223.9^{A}	167.6^{B}	128.7^{C}
CD value for comparing between species 1 and 2 =15.14 CD value for comparing between species 3 with 1 and 2 =17.48			

Note: Means with same small letter as superscript within a species are homogeneous
Means with same capital letter as superscript between species are homogeneous

Species averages in vessel diameter between species under study showed significant difference among each other. It was observed that Pterocarpus dalbergioides (223.9) accounted for higher value in vessel diameter followed by *Swietenia macrophylla* (167.6) and *Pericopsis mooniana* (128.7).

Pterocarpus dalbergioides showed an increasing trend in vessel diameter from pith towards periphery position with highest value in the periphery (282.3) position followed by middle (220.5) and pith (169) whereas vessel diameter in the middle (155.3) and pith (139.4) positions in *Swietenia macrophylla* was found to be similar with respect to periphery position (207.9). Apart from the other two species, *Pericopsis mooniana* did not show any significant difference in radial position for vessel diameter, and all the three position was found to homogeneous to each other.

4.2.1.3 Vessel frequency

4.2.1.3.1 Variation in vessel frequency between species as well as between positions within species

Analysis of variance conducted to study the vessel frequency between species and between radial positions within species among *P. dalbergioides*, *S. macrophylla* and *P. mooniana* showed that significant variation existed (table 19) between species with regard to vessel frequency at one percent level (figure 12 and 13).

Table 19. Variation in vessel frequency (no/mm^2) between species and between radial positions

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	2 (0.67)	7 (0.97)	6 (1.89)
Middle	1 (0.27)	6 (0.66)	5 (0.51)
Periphery	2 (0.55)	7 (28.926)	6 (1.09)
CD for comparing position	1.58	1.58	2.05
Species average	2^B	6^A	6^A
CD value for comparing between species 1 and 2 =0.91			
CD value for comparing between species 3 with 1 and 2 =1.06			

Means with the same capital letter as superscript between species are homogeneous

From table 19 it can be seen that radial variation within species not differed significantly for vessel frequency. *P. dalbergioides* showed a decreasing trend from the pith (2) towards middle (1) and thereafter increased towards periphery (2) region. Both *P. mooniana* and *S. macrophylla* showed the same trend of variation with regard to the vessel frequency. *P. mooniana* had values ranged from 5 (middle) to 6 (pith and periphery). In the case of *S. macrophylla* values ranged from 6 (middle) to 7 (pith and periphery).

4.2.1.4 Vessel length

4.2.1.4.1 Variation in vessel length between species as well as between positions within species

It was evident from table 20 that between species differed significantly at one percent level and radial variation within species was significant at 5 percent level with respect to vessel length (figure 12 and 13).

Table 20. Variation in vessel length (μm) between species and between radial positions

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	120.13^{b} (11.59)	102.23^{a} (25.12)	136.66^{a} (10.95)
Middle	145.52^{ab} (12.21)	123.21^{a} (30.08)	159.65^{a} (39.74)
Periphery	167.59^{a} (9.37)	106.81^{a} (18.57)	139.07^{a} (39.69)
CD for comparing position	29.38	29.38	37.93
Species average	120.13^{A}	102.23^{B}	136.66^{A}
CD value for comparing between species 1 and 2 =19.96			
CD value for comparing between species 3 with 1 and 2 =19.59			

Note: Means with same small letter as superscript within a species are homogeneous
Means with the same capital letter as superscript between species are homogeneous

Variation between species was found to be significant among different species under study. Species averages in *P. dalbergioides* as well as *P. mooniana* were found to be homogeneous to each other, whereas species averages in *S. macrophylla* (102.23) differed from *P. dalbergioides* (120.13) and *P. Mooniana* (136.66). In the case of *Pterocarpus dalbergioides* pith (120.13) and periphery (167.59) position differed significantly each other, whereas middle position (145.52) value was found to be at par with the pith and periphery position.

Higher value for vessel length was found in the periphery position in *Pterocarpus dalbergioides*. *Swietenia macrophylla* showed not much significant difference among the pith (102.23), middle (123.21) and periphery (106.81) positions with respect to vessel length. Similarly *P. mooniana* also showed not much significant difference among pith (136.66), middle (159.65) and periphery (139.07) positions.

4.2.2 Ray morphology

4.2.2.1 Ray height

4.2.2.1.1 Variation in ray height between species as well as between positions within species

Analysis results given in table 21 showed that there was significant difference (1%) existed between as well as within species for ray height at one percent level (figure 14 and 15).

Table 21. Variation in ray height (μm) between species and between radial positions within species

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	193.3[a] (19.4)	467.6[b] (46.9)	310.8[a] (39.6)
Middle	182.3[a] (17.2)	539.9[a] (71.9)	328.8[a] (18.4)
Periphery	176.9[a] (21.2)	539.4[a] (66.3)	302.1[a] (24.4)
CD for comparing position	56.03	56.03	64.70
Species average	184.2[C]	515.6[A]	313.9[B]
CD value for comparing between species 1 and 2 =32.35 CD value for comparing between species 3 with 1 and 2 =37.35			

Note: Means with same superscripts within a species are homogeneous
Means with same superscripts between species are homogeneous

Fig. A

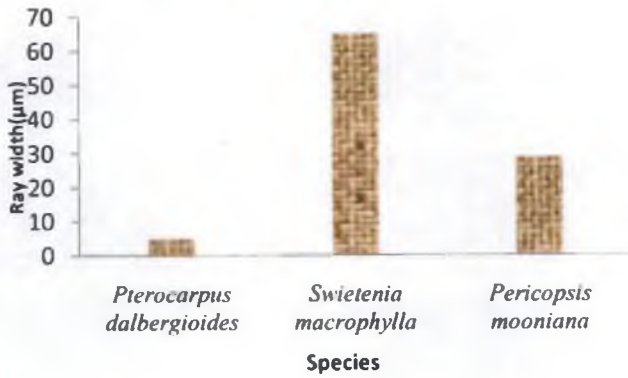


Fig. B

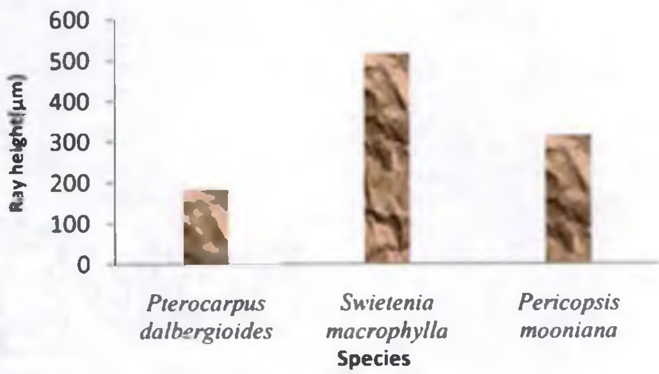


Fig. C

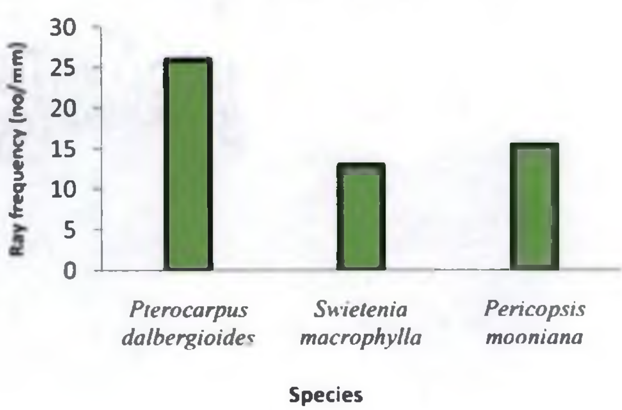
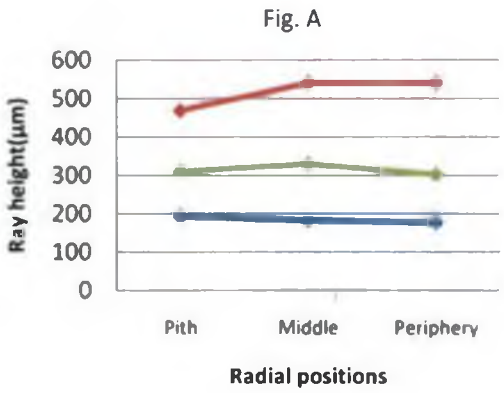
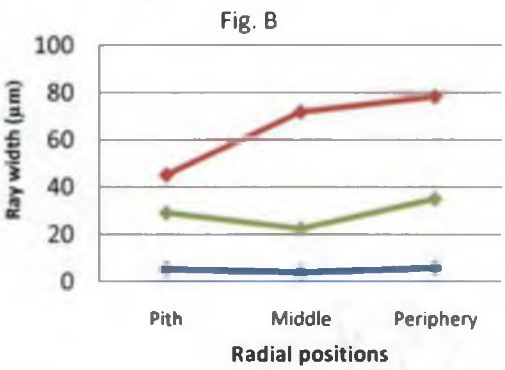


Fig 14. Variation in (A) Ray width; (B) Ray height; (C) Ray frequency between species





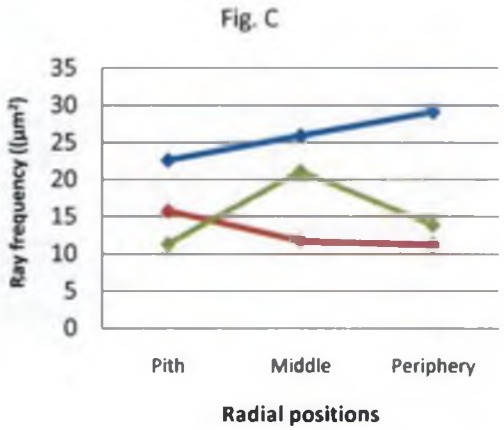


Fig 15. Radial variation in (A) Ray height (B) Ray width and (C) Ray frequency within species

Pericopsis mooniana ; *Swietenia macrophylla* ; *Pterocarpus dalbergioides*

Variation between species differed significantly with regard to ray height with highest species average was found in *Swietenia macrophylla* (515.6) followed by *Pericopsis mooniana* (313.9) and *Pterocarpus dalbergioides* (184.2).

Fig.14 and 15 illustrates the variation pattern in ray height between species and between radial positions within species. In the case of *Pterocarpus dalbergioides* pith (193.3), middle (182.3) and periphery (176.9) were found to have homogeneous values with respect to ray height. Similarly, *Pericopsis mooniana* followed the same pattern for species averages with homogeneous values for the pith (310.8), middle (328.8) and periphery (302.1) positions. Pith (467.6) position differed significantly from middle (539.9) and periphery (539.4) in the case of *Swietenia macrophylla,* whereas middle and periphery position showed similar values.

4.2.2.2 Ray width

4.2.2.2.1 Variation in ray width between species as well as between positions within species

Ray width followed highly significant variation (1% level) between species as well as between radial positions within species (figure 14 and 15). Results are presented in table 22.

Table 22. Variation in ray width (µm) between species and between radial positions within species

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	5.3^a (1.7)	45.0^b (14.4)	29.1^a (6.4)
Middle	3.8^a (1.1)	71.7^a (9.5)	22.3^a (7.8)
Periphery	5.8^a (1.0)	78.2^a (14.2)	34.9^a (6.2)
CD for comparing position	11.29	11.29	14.57
Species average	4.9^C	64.9^A	28.7^B
CD value for comparing between species 1 and 2 =6.52			
CD value for comparing between species 3 with 1 and 2 =7.53			

Note: Means with the same small letter as superscript within a species are homogeneous
Means with the same capital letter as superscript between species are homogeneous

Species averages in ray width were significant between species. Highest species average in ray width were noticed in *S. macrophylla* (64.9) followed by *Pericopsis mooniana* (28.7) and *Pterocarpus dalbergioides* (4.9).

Radial variation within species showed highly significant difference at one percent level. *Pterocarpus dalbergioides* showed similar values for ray width in pith (5.3), middle (3.8) and periphery position (5.8). Similarly, *Pericopsis mooniana* was also found to have homogeneous values for ray width in the pith (29.1), middle (22.3) and periphery (34.9) position. In the case of *Swietenia macrophylla*, ray width showed a significant difference in the pith (45) position compared to the periphery region (78.2) and middle (71.7).

4.2.2.3 Ray frequency

4.2.2.3.1 Variation in ray frequency between species as well as between positions within species

Variation between species and radial variation within species with regard to ray frequency are presented in table 23.

Table 23. Variation in ray frequency (no/mm^2) between species and between radial positions

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	22.6^b (2.8)	15.7^a (2.4)	11.3^b (2.1)
Middle	25.9^{ab} (3.4)	11.7^a (1.2)	21.1^a (13.9)
Periphery	29.1^a (3.7)	11.2^a (1.9)	13.8^{ab} (1.4)
CD for comparing position	5.65	5.65	7.29
Species average	25.9^A	12.9^B	15.4^B
CD value for comparing between species 1 and 2 =3.26 CD value for comparing between species 3 with 1 and 2 =3.77			

Note: Means with the superscripts within a species are homogeneous
Means with the same superscripts between species are homogeneous

Analysis results revealed that significant differences existed for ray frequency among species (1% level) and between radial positions within species at 5 percent level (figure 14 and 15). Between species showed a significant variation in ray frequency with highest species average was found in *P. dalbergioides* (25.9). *S. macrophylla* (12.9) and *P. mooniana* (15.4) showed homogeneous values in ray frequency.

From table 23, it can be seen that periphery position (29.1) showed highest value for ray frequency in *Pterocarpus dalbergioides*. Moreover, periphery and pith (22.6) were found to have significant differences in vessel frequency whereas middle position (25.9) was homogeneous with the pith and periphery region. In *Swietenia macrophylla* pith (15.7), middle (11.7) and periphery (11.2) position were found to be at par for ray frequency. *Pericopsis mooniana* showed a significant difference among the radial position.

4.2.3 Fibre morphology

4.2.3.1 Fibre length

4.2.3.1.1 Variation in fibre length between species as well as between positions within species

Summarised data on variation between species and between radial positions within species for fibre length are presented in table 24. Analysis of variance revealed that variation in species averages in fibre length differed significantly at one percent level. *P. dalbergioides* (976.4) showed significant difference in fibre length compared to *S. macrophylla* (1311.1) and *P. mooniana* (1240.1), whereas the later two species showed homogeneous values for fibre length (figure 16 and 17).

Radial variation among different species under study were found to be non-significant to each other with respect to fibre length. In the case of *P. dalbergioides* value ranged from 842.1 (pith) to 1071.9 (periphery) and showed an increasing trend from the pith towards periphery position.

S. macrophylla showed decreasing fibre length values from pith (1298.9) to middle (1297.4) and then showed an increasing trend from middle to periphery position (1337.0). In the case of *P. mooniana*, decreasing trend was observed from pith (1327.3) towards periphery (1170.1).

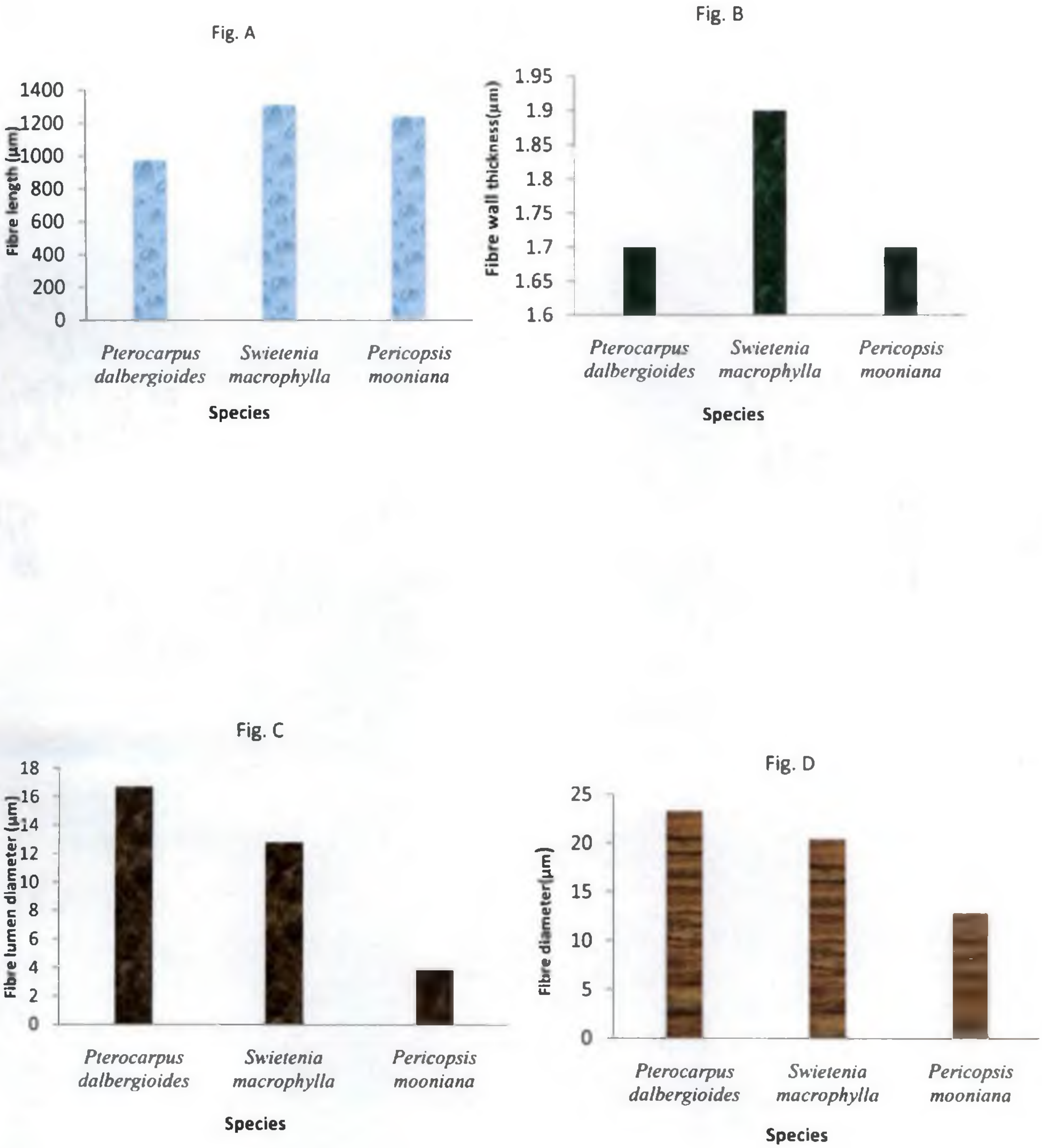


Fig 16. Variation in (A) Fibre length; (B) Fibre wall thickness; (C) Fibre lumen diameter and (D) Fibre diameter between species

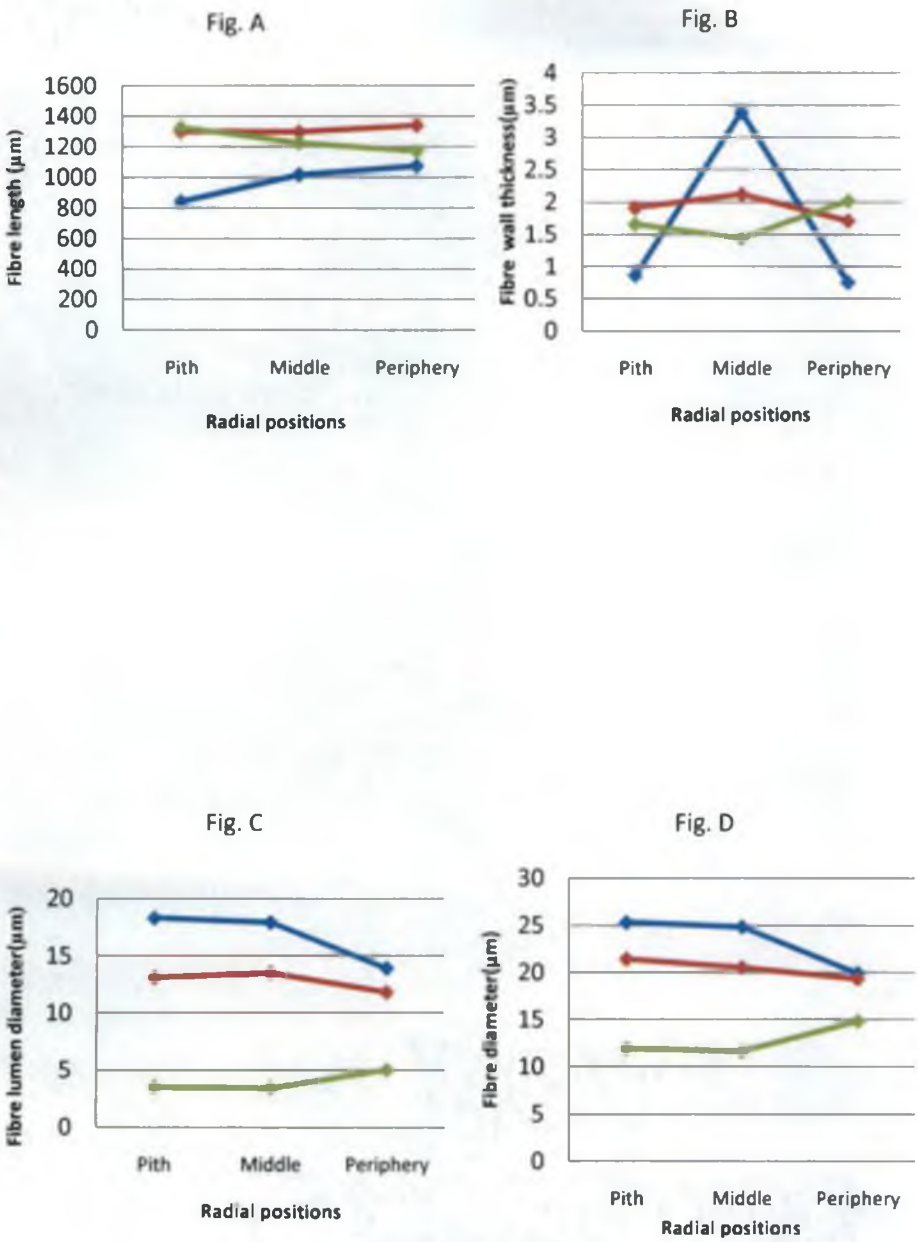


Fig 17. Radial variation in (A) Fibre length; (B) Fibre wall thickness; (C) Fibre lumen diameter and (D) Fibre diameter within species

Pericopsis mooniana ; *Swietenia macrophylla* ; *Pterocarpus dalbergioides*

Table 24. Variation in fibre length (μm) between species and between radial positions

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	842.1 (130.7)	1298.9 (118.3)	1327.3 (117.7)
Middle	1015.4 (161.7)	1297.4 (80.3)	1222.9 (131.5)
Periphery	1071.9 (118.3)	1337.0 (196.2)	1170.1 (63.4)
CD for comparing position	278.21	278.21	359.17
Species average	976.4^B	1311.1^A	1240.1^A
CD value for comparing between species 1 and 2 =160.63 CD value for comparing between species 3 with 1 and 2 =185.48			

Note: Means with same superscripts between species are homogeneous

4.2.3.2 Fibre wall thickness

4.2.3.2.1 Variation in fibre wall thickness between species as well as between positions within species

The result of NESTED ANOVA in fibre wall thickness for the three different species under study are summarised in table 25. Between species comparison showed that species averages for fibre wall thickness were found to be non-significant among each other with regard to fibre wall thickness. However, higher value for fibre wall thickness was found in *S. macrophylla* (1.9) whereas *P.dalbergioides* and *P. mooniana* showed same value (1.7) for fibre wall thickness (figure 16 and 17).

Result of analysis of variance revealed that there was no statistically significant difference between the radial positions within a species and between species. *P. dalbergioides* showed an increase in value from pith (0.86) to middle (3.39), and then showed a decrease in value towards periphery (0.75). Similarly *S. macrophylla* also showed the same pattern of radial variation with an increase in value from pith (1.91) to middle (2.12) and later showed a decline towards periphery (1.71). *P. mooniana* showed a different pattern of variation with a decreasing value from pith (1.66) to middle (1.44), and then showed an increase towards periphery (2.02).

Table 25. Variation in fibre wall thickness (μm) between species and between radial positions

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	0.86 (0.66)	1.91 (0.74)	1.66 (0.28)
Middle	3.39 (6.06)	2.12 (0.94)	1.44 (0.62)
Periphery	0.75 (0.31)	1.71 (0.25)	2.02 (0.16)
CD for comparing position	3.97	3.97	5.12
Species average	1.7	1.9	1.7
CD value for comparing between species 1 and 2 =2.29 CD value for comparing between species 3 with 1 and 2 = 2.64			

4.2.3.3 Fibre lumen diameter

4.2.3.3.1 Variation in fibre lumen diameter between species as well as between positions within species

Summarised data on variation between species and radial variation in fibre lumen diameter within species are presented in table 26. Analysis of variance conducted revealed that between species differ significantly with respect to fibre lumen diameter (1%), whereas radial variation within species under study were found to be non significant to each other (figure 16 and 17).

Variation in species averages for fibre lumen diameter differed significantly among different species under study. *P. dalbergioides* (16.7) showed the highest value for fibre lumen diameter, followed by *S. macrophylla* (12.8) and *P. mooniana* (3.9).

Table 26. Variation in fibre lumen diameter (µm) between species and between radial positions

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	18.3 (4.1)	13.1 (2.0)	3.5 (0.9)
Middle	17.9 (8.0)	13.5 (3.3)	3.4 (1.3)
Periphery	13.9 (1.0)	11.8 (1.9)	5.0 (0.6)
CD for comparing position	6.43	6.43	8.30
Species average	16.7^{A}	12.8^{B}	3.9^{C}
CD value for comparing between species 1 and two 3.71 CD value for comparing between species 3 with 1 and 2 = 4.28			

Note: Means with the same superscripts between species are homogeneous

From table 26, it was evident that *P. dalbergioides* had values ranged from 13.9 (periphery) to 18.3 (pith) and it showed decreasing trend from the pith towards periphery region. *S. macrophylla* showed an initial increase of fibre lumen diameter from pith (13.1) to middle (13.5) and then showed a decline from middle to periphery position (11.8). In the case of *P. mooniana,* decreasing trend was observed from pith (3.5) to the middle (3.4) later showed an increasing trend towards periphery.

4.2.3.4 Fibre diameter

4.2.3.3.1 Variation in fibre diameter between species as well as between positions within species

The results of analysis of variance (table 27) in fibre diameter revealed that between species variation was significant (1%) with respect to fibre lumen diameter and radial variation within species were found to be non significant (figure 16 and 17).

Between species comparison showed that species averages for fibre lumen diameter were found to be similar in *P. dalbergioides* (23.3) and *S. macrophylla* (20.4), whereas *P. mooniana* (12.8) was significantly differed from the above two species for fibre lumen diameter.

Table 27. Variation in fibre diameter (µm) between species and between radial positions within species

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	25.3 (4.1)	21.4 (2.8)	11.9 (1.5)
Middle	24.8 (8.9)	20.5 (2.9)	11.6 (2.4)
Periphery	19.9 (2.1)	19.3 (2.7)	14.8 (0.8)
CD for comparing position	7.21	7.21	9.31
Species average	23.3^{A}	20.4^{A}	12.8^{B}
CD value for comparing between species 1 and 4.16 CD value for comparing between species 3 with 1 and 2 = 4.81			

Note: Means with the same capital letter as superscript between species are homogeneous

A decreasing trend from pith towards periphery was observed in *P. dalbergioides* and the value ranged from 25.3 (pith) to 19.9 (periphery). Similarly *S. macrophylla* showed the same pattern of radial variation with a decreasing trend from pith (21.4) towards periphery (19.3) position for the fibre lumen diameter. *P. mooniana* was also found to have the same radial pattern of decreasing lumen diameter value from pith (11.9) to middle (11.6) then increased to periphery (14.8).

4.2.4 Tissue proportions

4.2.4.1 Ray percent

4.2.4.1.1 Variation in ray percent between species as well as between positions within species

Variation between tree species in ray percent for *Pterocarpus dalbergioides, Swietenia macrophylla* and *Pericopsis mooniana* as well as within tree variation were found to be significant at one percent level. The results are illustrated in table 28 (figure 18 and 19).

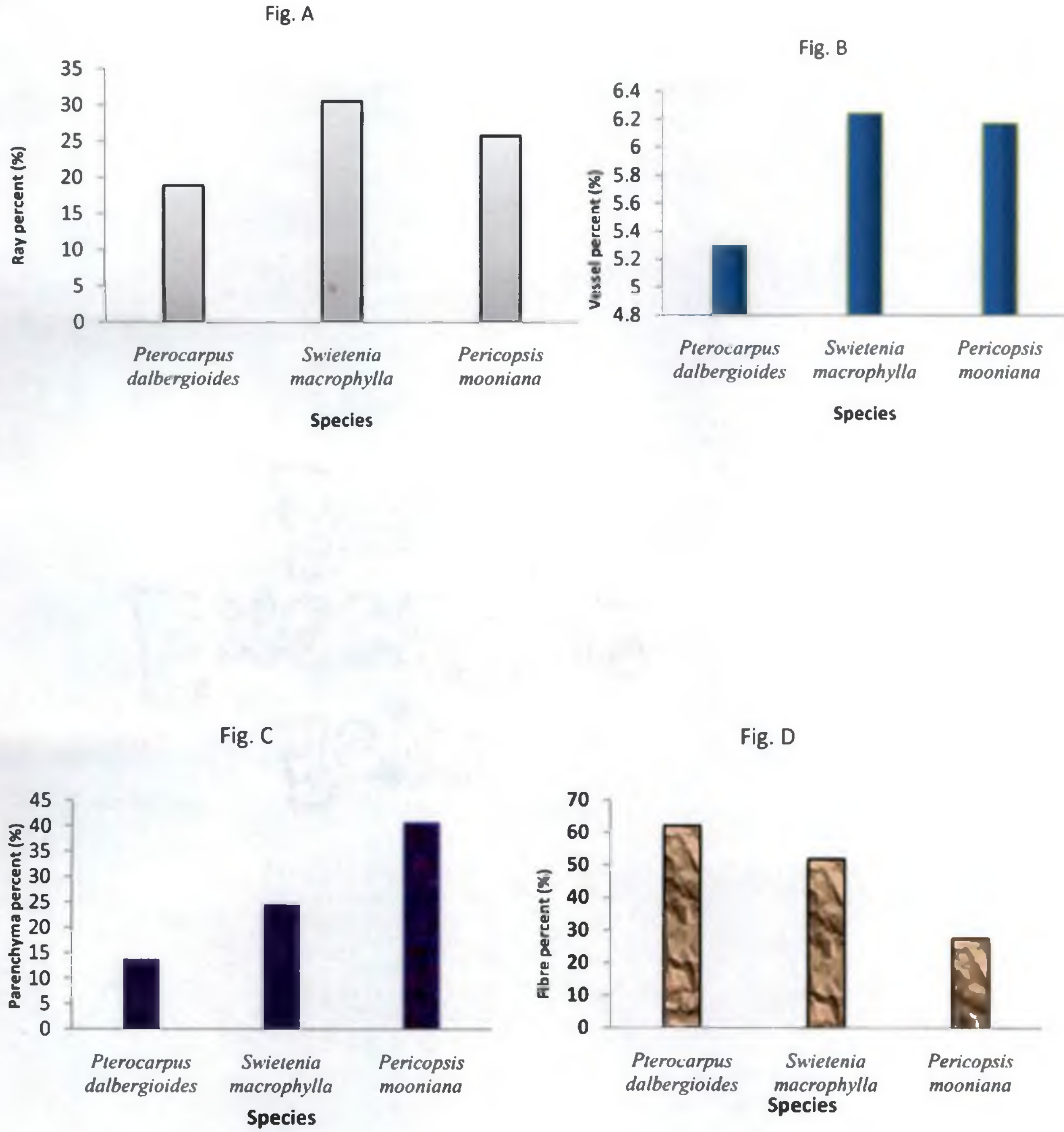


Fig 18. Variation in (A) Ray percent; (B) Vessel percent; (C) Parenchyma percent and (D) Fibre percent between species

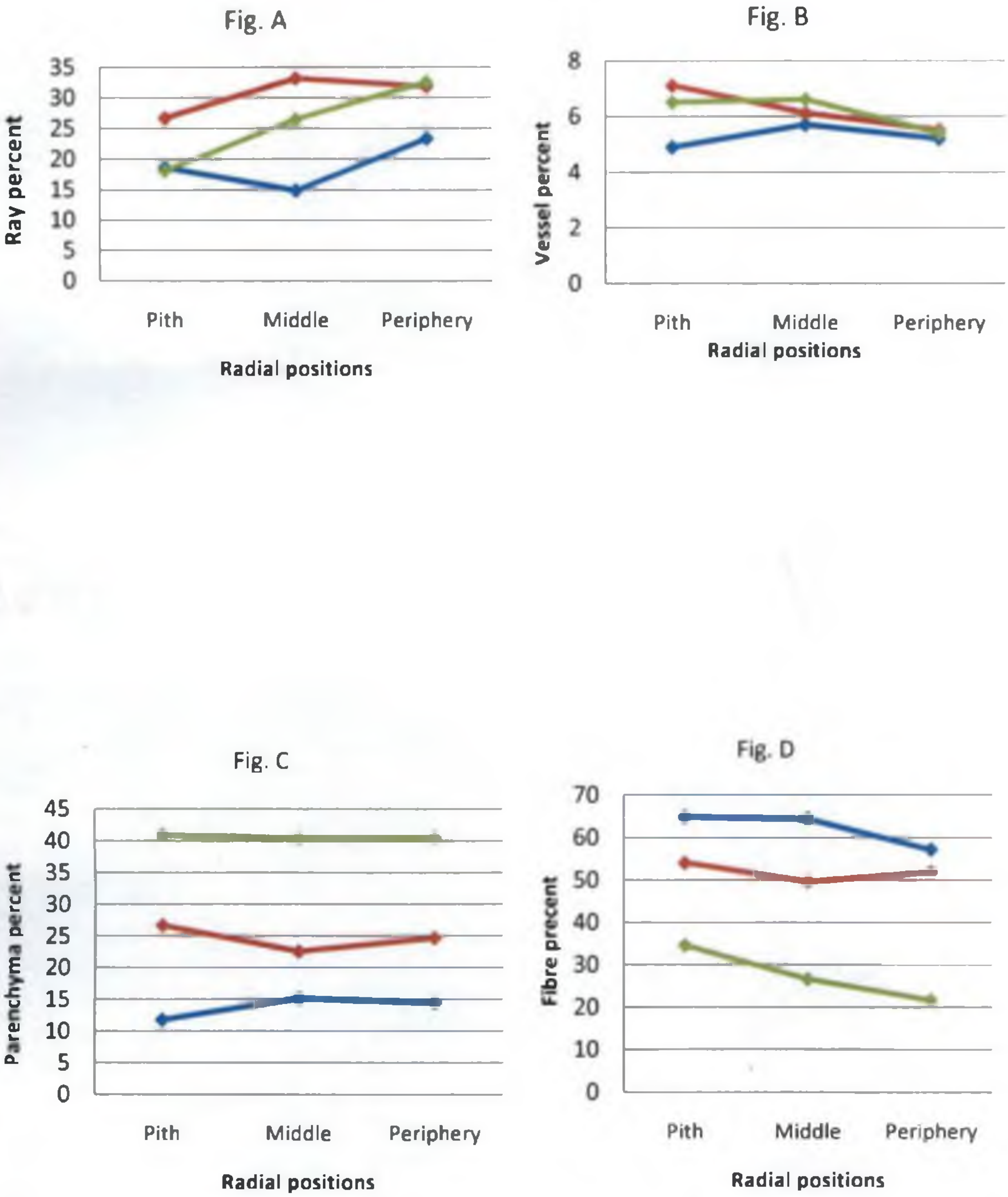


Fig 19. Radial variation in (A) Ray percent; (B) Vessel percent; (C) Parenchyma percent and (D) Fibre percent within species

Pericopsis mooniana —●— ; *Swietenia macrophylla* —◆— ; *Pterocarpus dalbergioides* —◆—

Table 28. Variation in ray percent (%) between species and between radial positions within species

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	18.59^{a} (2.54)	26.64^{a} (6.63)	18.11^{b} (2.08)
Middle	14.87^{a} (3.43)	33.16^{a} (5.17)	26.47^{ab} (5.90)
Periphery	23.35^{a} (3.65)	31.81^{a} (9.36)	32.56^{a} (3.31)
CD for comparing position	9.31	9.31	12.02
Species average	18.9^{B}	30.5^{A}	25.7^{A}
CD value for comparing between species 1 and 5.38 CD value for comparing between species 3 with 1 and 2 = 6.21			

Note: Means with the same superscripts within a species are homogeneous
Means with the same superscripts between species are homogeneous

Species average in ray percent among three species under study showed significant difference (1%) in ray percent. Only *P. dalbergioides* (18.9) differed significantly from S. *macrophylla* (30.5) and *P. mooniana* (25.7). The latter two species found to be homogeneous each other with respect to ray percent value.

Pterocarpus dalbergioides showed no significant difference among the radial position and the value was found to be similar among radial positions. The value ranges from 14.87 (middle) to 23.35 (periphery). Similarly *S. macrophylla* showed homogeneous values among the radial position and it ranges from 26.64 (pith) to 33.16 (middle) position.

There was significant difference among the pith (18.11) and periphery (32.56) position in ray percent for *P. mooniana* whereas, middle position (26.47) showed homogeneous value with the pith and periphery position with respect to ray percent.

4.2.4.2 Vessel percent

4.2.4.2.1 Variation in vessel percent between species and between positions within species

Analysis of variance revealed that (table 29) no significant difference existed in vessel percent between species as well as between positions within species among different species under study (figure 18 and 19). Table 29 showed that between species difference was non-significant with regard to the vessel percent. Species average ranged from 5.3 (*P. dalbergioides*) to 6.17 (*P. mooniana*). Species average in *S. macrophylla* for vessel percent was 6.17.

The analysis result for radial variation within species showed that (table 13) no significant radial variation existed within species. *P. dalbergioides* showed an increasing trend towards middle (5.7) from pith (4.9) and thereafter found to be decreased towards the periphery (5.2) position. *P. mooniana* showed the same pattern of increasing trend towards middle (6.6) from pith (6.5) and later a declining trend towards periphery (5.4) position. S. *macrophylla* was found to have a decreasing trend from pith (7.1) towards periphery (5.5).

Table 29. Variation in vessel percent between species and between radial positions within species

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	4.9 (1.1)	7.1 (1.6)	6.5 (2.0)
Middle	5.7 (1.0)	6.1 (0.8)	6.6 (1.5)
Periphery	5.2 (1.1)	5.5 (1.3)	5.4 (0.6)
CD for comparing position	2.17	2.17	2.80
Species average	5.3	6.24	6.17
CD value for comparing between species 1 and 1.25 CD value for comparing between species 3 with 1 and 2 = 1.45			

4.2.4.3 Parenchyma percent

4.2.4.3.1 Variation in parenchyma percent between species and between radial positions within species

Variation in species average with regard to parenchyma percent between species and radial variation within species are summarised in table 30 (figure 18 and 19).

From table 30 it can be seen that parenchyma percent between species differed significantly (1%). Highest species average in parenchyma percent was found in *P. mooniana* (40.59), followed by *S. macrophylla* (24.54) and *P. dalbergioides* (13.7).

Variation in radial position within species was found to be non significant. *P. dalbergioides* showed an increasing parenchyma percent from the pith (11.7) towards middle (15.1), and thereafter showed a decreasing trend towards periphery (14.4). *S. macrophylla* had values that ranged from 22.5 (middle) to 26.6 (pith). In *P. mooniana* it ranged from 40.4 (middle) to 40.9 (pith).

Table 30. Variation in parenchyma percent between species and between radial positions

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	11.7 (3.0)	26.6 (8.2)	40.9 (13.8)
Middle	15.1 (2.4)	22.5 (5.9)	40.4 (11.2)
Periphery	14.4 (4.4)	24.6 (7.6)	40.5 (3.8)
CD for comparing position	12.03	12.03	15.54
Species average	13.7^{C}	24.54^{B}	40.59^{A}
CD value for comparing between species 1 and 6.95 CD value for comparing between species 3 with 1 and 2 = 8.02			

Note: Means with same capital letter as superscript between species are homogeneous

4.2.4.4 Fibre percent

4.2.4.4.1 Variation in fibre percent between species and between positions within species

Result of NESTED ANOVA for comparing species averages among *Pericopsis mooniana, Swietenia macrophylla* and *Pterocarpus dalbergioides* and radial variation within species are illustrated in table 31(figure 18 and 19).

It can be seen that fibre percent was significantly differed among the species under study (1%). *P. dalbergioides* (62.1) showed highly significant difference with respect to fibre percent followed by *S. macrophylla* (51.8) and *P. mooniana* (27.5).

From table 31 it was noticed that radial variation in fibre percent within species was non-significant. The value for fibre percent in *P. dalbergioides* ranged from 57.07 (periphery) to 64.85 (pith). *S. macrophylla* had values that ranged from 49.56 (middle) to 54.01 (pith). In the case of *P. mooniana* value ranged from 21.52 (periphery) to 34.52 (pith).

Table 31. Variation in fibre percent between species and between radial positions within species

Radial positions	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*
Pith	64.85 (4.58)	54.01 (10.96)	34.52 (13.65)
Middle	64.36 (5.76)	49.56 (5.39)	26.53 (13.87)
Periphery	57.07 (2.34)	51.79 (7.11)	21.52 (6.89)
CD for comparing position	15.83	15.83	20.43
Species average	62.1^{A}	51.8^{B}	27.5^{C}
CD value for comparing between species 1 and 9.14 CD value for comparing between species 3 with 1 and 2 = 10.55			

Note: Means with the superscripts between species are homogeneous

4.3 MECHANICAL PROPERTIES

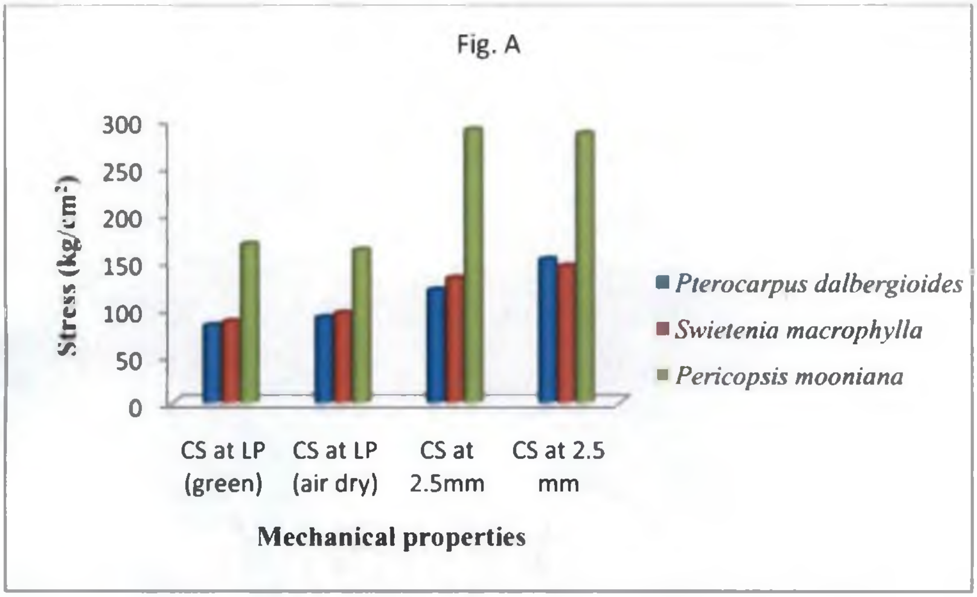
4.3.1 Compressive strength perpendicular to the grain

4.3.1.1 Compressive strength perpendicular to the grain at green condition

4.3.1.1a Compressive stress at limit of proportionality (CS at LP) at green condition

Compressive stress at limit of proportionality is given in table 32 and figure 20. The values show significant difference between species at green condition.

Compressive stress at limit of proportionality at green condition was found to be higher in *Pericopsis mooniana* (167.11 kg/cm^2), and the value was significantly different from the other two species viz., *S. macrophylla* (85.87) and *P. dalbergioides* (81.56). Moreover, CS at LP value for *S. macrophylla* and *P.dalbergioides* was found to be at par. When compared with teak (86), at green condition, the CS at LP value was higher in



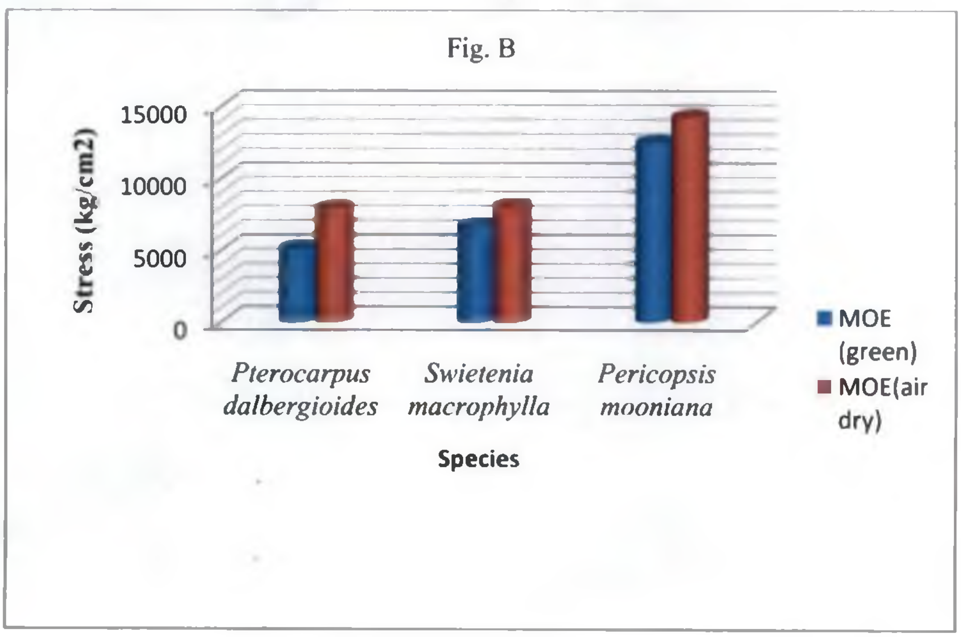


Fig 21. Comparison of compressive strength perpendicular to the grain test between species: (A) Green condition; (B) Air dry condition

P. mooniana where as *P. dalbergioides* and *S. macrophylla* showed a lower value for CS at LP.

Table 32. Compressive stress at limit of proportionality (CS at LP) of P. *dalbergioides, S. macrophylla and Pericopsis mooniana* at green and air dry condition

Sl. No	Species	CS at LP (kg/ cm^2)	
		Green	Air dry
1	*Pterocarpus dalbergioides*	81.56^b	90.17^b
2	*Swietenia macrophylla*	85.87^b	94.77^b
3	*Pericopsis mooniana*	167.11^a	160.87^a
4	*Tectona grandis* (taken as standard for comparison)	86.00	101.00
CD for comparing species 1 and 2			
CD for comparing species 1 and 2 with 3			

Means column wise comparison
Values with same superscript do not differ significantly between themselves

4.3.1.1b Compressive stress at limit of proportionality (air dry condition)

Table 32 showed that values of CS at LP were significant (1% level) between species. CS at LP value in air dry condition for *P. dalbergioides* (90.17) was found to be at par with *S. macrophylla* (94.77), but was significantly different from *P.mooniana* (160.87). *P. mooniana* showed the highest value (160) for CS at LP at air dry condition. Compared to teak (101), *Pericopsis mooniana* (160.87) showed higher value for CS at LP, whereas *P. dalbergioides* and *S. macrophylla* showed lower values than teak for CS at LP at air dry condition.

4.3.1.2 Compressive stress at 2.5 mm deflection

4.3.1.2a Compressive stress at 2.5 mm deflection (green condition)

CS at 2.5 mm deflection showed significant difference between species (1%). It was observed that CS at 2.5 mm deflection in green condition for *P. mooniana* (288.50) differed from *S. macrophylla* (131.88) and *P. dalbergioides* (118.88) which were at par (table 33).

Table 33. Compressive stress at 2.5 mm deflection in P. *dalbergioides, S. macrophylla and Pericopsis mooniana* at green and air dry condition

SI. No	Species	CS at 2.5mm ($kgcm^{-2}$)	
		Green	Air- dry
1	*Pterocarpus dalbergioides*	118.88^{b}	150.89^{b}
2	*Swietenia macrophylla*	131.22^{b}	143.80^{b}
3	*Pericopsis mooniana*	288.50^{a}	284.62^{a}
CD for comparing species 1and 2		84.71	97.5
CD for comparing species 1 and 2 with 3		91.65	105.5

Means column wise comparison
Values with same superscript do not differ significantly between themselves

4.3.1.2b Compressive stress at 2.5 mm deflection (air dry condition)

CS at 2.5 mm deflection values at air dry condition differed (1%) greatly among the studied species. *Pericopsis mooniana* (284.62) was found to have higher value for CS at 2.5 mm deflection and differed significantly from *S. macrophylla* (143.80) and *P. dalbergioides* (150.89). Moreover the values in *S. macrophylla* and *P. dalbergioides* were at par.

4.3.1.3 Modulus of elasticity (MOE) at green and air dry condition

4.3.1.3a Modulus of elasticity (MOE) at green condition

Variation in modulus of elasticity (MOE) among species was significant (1%) at green condition (Table 34). *P. mooniana* (12461.21) showed highest value for MOE and differed significantly from the other two species. *P. dalbergioides* (5103.36) and *S. macrophylla* (6648.95) showed similar values.

Table 34. Modulus of elasticity (MOE) of P. *dalbergioides, S. macrophylla and Pericopsis mooniana* at green and dry condition

SI. No	Species	MOE (kg/cm^2)	
		Green	Air- dry
1	*Pterocarpus dalbergioides*	5103.36^{b}	7887.98^{b}
2	*Swietenia macrophylla*	6648.95^{b}	8051.74^{b}
3	*Pericopsis mooniana*	12461.21^{a}	14238.99^{a}
CD for comparing species 1 and 2		3841.69	4422.12
CD for comparing species 1 and 2 with 3		3863.64	4447.39

Means column wise comparison
Values with same superscript do not differ significantly between themselves

4.3.1.3b Modulus of elasticity (MOE) at air dry condition

Modulus of elasticity values in *P. dalbergioides*, *S. macrophylla* and *P. mooniana* were also found to be significantly different (1%) at air dry condition (Table 34). *P. mooniana* (14238.99) showed highest value for MOE and differed significantly from the other two species viz., *P. dalbergioides* (7887.98) and *S. macrophylla* (8051.74) which were at par.

4.3.2 Compressive strength parallel to grain

4.3.2.1 Compressive stress at limit of proportionality (CS at LP) at green and air-dry condition

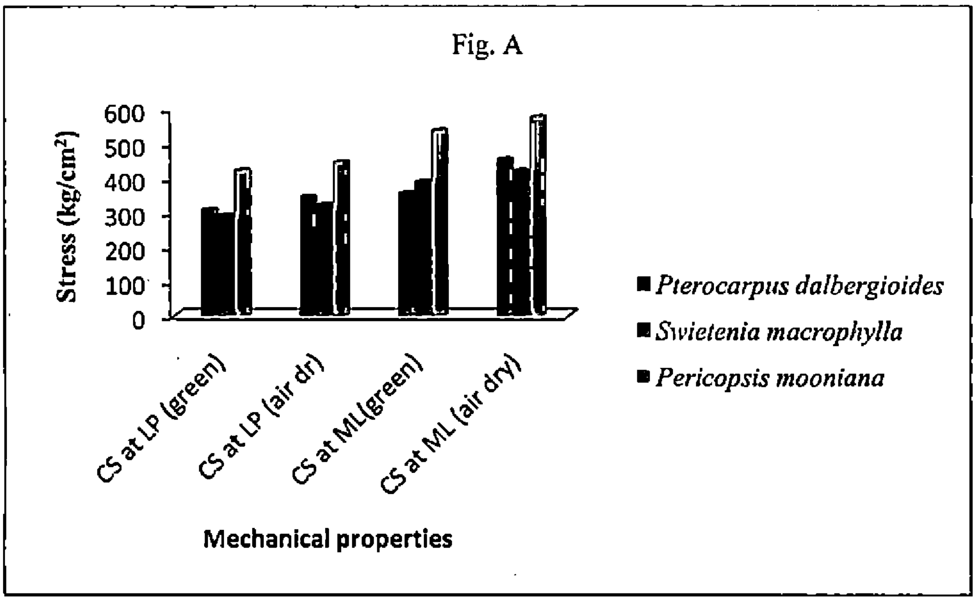
4.3.2.1a Compressive stress at limit of proportionality (CS at LP) in green condition

CS at LP in compressive strength parallel to grain test at green condition showed significant difference (5%) between the different species studied. Results are illustrated in table 35 and figure 21. *P. mooniana* (420.92) differed greatly for CS at LP when compared to *S. macrophylla* (289.33) and *P. dalbergioides* (305.55). The latter two species showed homogeneous values for CS at LP in green condition. CS at LP value for *P. mooniana* was higher than teak (311) at green condition, whereas the latter two species showed values which were lower than that of teak.

Table 35. Compressive stress at limit of proportionality of P. *dalbergioides, S. macrophylla* and *Pericopsis mooniana* at green and dry condition

SI. No	Species	CS at LP (kg/cm^2)	
		Green	Air dry
1	*Pterocarpus dalbergioides*	305.55^b	343.68
2	*Swietenia macrophylla*	289.33^b	319.94
3	*Pericopsis mooniana*	420.92^a	444.32
4	*Tectona grandis* (taken as standard for comparison)	311.00	376.00
CD for comparing species 1 and 2		91.18	----
CD for comparing species 1 and 2 with 3		104.95	----

Means column wise comparison
Values with same superscript do not differ significantly between themselves



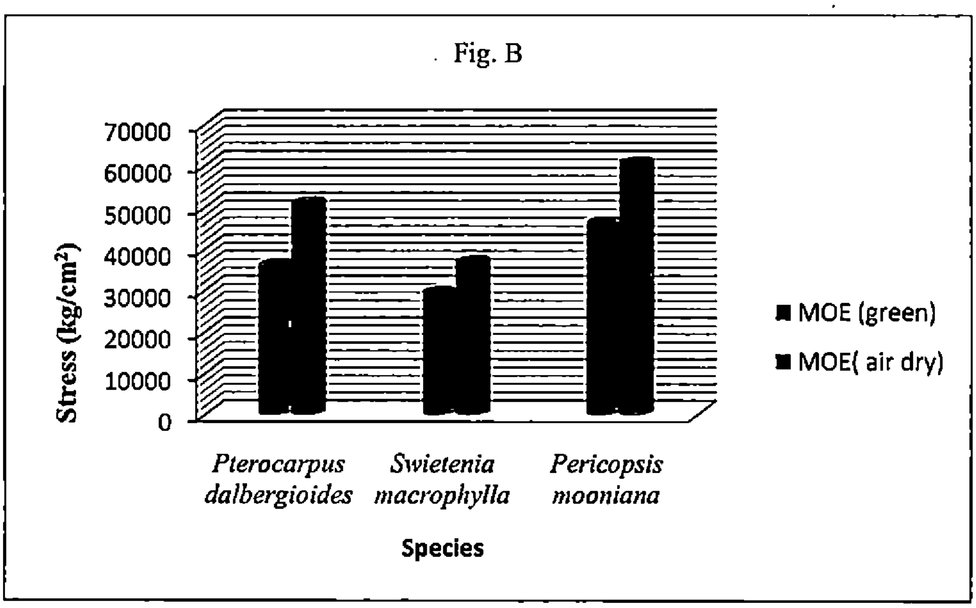


Fig 20. Comparison of compressive strength parallel to the grain test between species

4.3.2.1b Compressive stress at limit of proportionality (CS at LP) at air dry condition

CS at LP values at air dry condition did not vary significantly among the species studied (table 35). CS at LP value ranged from 319.95 (*S. macrophylla*) to 444.32 (*P. mooniana*). *P. dalbergioides* was found to have a value of 343.68 for CS at LP in the air dry condition. CS at LP value of *P. mooniana* was higher than CS at LP value of teak (376) at air dry condition. *S. macrophylla* and *P. dalbergioides* were found to have lower value compared to teak with regard to CS at LP in air dry condition.

4.3.2.2 Compressive stress at maximum load (CS at ML) in green and air dry condition

4.3.2.2a Compressive stress at maximum load in green condition

CS at ML at green condition in *P. dalbergioides, S. macrophylla* and *P. mooniana* are illustrated in table 36. *Pericopsis mooniana* (536.71) showed the highest value for CS at ML at green condition and differed significantly (5%) from the two other species. *S. macrophylla* (387.02) and *P. dalbergioides* (353.77) did not differ significantly between each other with respect to the CS at ML value at green condition and were at par. Compared to CS at ML value for teak (415), *P. mooniana* showed higher value (536.71) at green condition, while the other two species under study showed a lower value compared to teak.

Table 36. Compressive stress at maximum load (CS at ML) of *P. dalbergioides, S. macrophylla and Pericopsis mooniana* at green and dry condition

S. No	Species	CS at ML ($kgcm^{-2}$)	
		Green	Air dry
1	*Pterocarpus dalbergioides*	353.77^{b}	452.71^{b}
2	*Swietenia macrophylla*	387.02^{b}	419.65^{b}
3	*Pericopsis mooniana*	536.71^{a}	574.48^{a}
4	*Tectona grandis* (taken as standard for comparison)	415.00	532.00
CD for comparing species 1 and 2		115.32	
CD for comparing species 1 and 2 with 3		132.74	

Means column wise comparison
Values with same superscript do not differ significantly between themselves

4.3.2.2b Compressive stress at maximum load in air dry condition

CS at ML values at air dry condition was found to have no significant difference between tree species in this study. Compared to *S. macrophylla* (419.65) and

P. dalbergioides (452.71), *P. mooniana* (574.48) which had values were even higher than teak (532) as reported by Sekhar (1988).

4.3.2.3 Modulus of elasticity (MOE) in green and air dry condition

4.3.2.3a Modulus of elasticity in green condition

Values for MOE at green condition were found to be significant among all the species under study. *P.mooniana* (45884.29) showed significantly higher value for MOE at green condition (table 37). *S. macrophylla* (29172.13) and *P. dalbergioides* (35808.06) were significantly differed from *P. mooniana*, whereas, both of them were at par in green condition. When compared to MOE at green condition for teak, all the species under study showed lower value for MOE.

Table 37. Modulus of elasticity (MOE) of P. *dalbergioides, S. macrophylla and Pericopsis mooniana* at green and dry condition

SI. No	Species	MOE ($kgcm^{-2}$)	
		Green	Air- dry
1	*Pterocarpus dalbergioides*	35808.06^{b}	50657.76^{b}
2	*Swietenia macrophylla*	29172.13^{b}	36532.81^{c}
3	*Pericopsis mooniana*	45884.29^{a}	60289.15^{a}
4	*Tectona grandis* (taken as standard for comparison)	129800.00	137400.00
CD for comparing species 1 and 2		7419.22	6548.99
CD for comparing species 1 and 2 with 3		8540.16	7538.45

Means column wise comparison

Values with same superscript do not differ significantly between themselves

4.3.2.3b Modulus of elasticity in air dry condition

Variations between species were significantly differed among the three species studied. *P. mooniana* showed the highest value (60289.15), followed by *P. dalbergioides* (50657.76) and *S. macrophylla* (36532.81) with regard to MOE at air dry condition. MOE values at air dry condition was found to be very low for all the three species compared to teak, as reported by Sekhar (1988).

4.3.3 Static bending test at green and air dry condition

4.3.3.1 Modulus of rupture at green and air dry condition

4.3.3.1a Modulus of rupture at green condition

Modulus of rupture at green condition in *P. mooniana* (1152.13) was found to be significantly different (1%) from *S. macrophylla* (667.54) and *P. dalbergioides* (733.43) showed highest value for MOR at green condition. Its value was found to be higher than that of teak (841) as reported by Sekhar (1988). The results are illustrated in table 38 and figure 22. MOR values at green condition in *S. macrophylla* and *P. dalbergioides* were found to be at par and were found to be lower than teak.

Table 38. Modulus of rupture (MOR) of *P. dalbergioides, S. macrophylla and Pericopsis mooniana* at green and dry condition

S. No	Species	MOR(kg/cm^2)	
		Green	Air- dry
1	*Pterocarpus dalbergioides*	733.43[b]	849.81[b]
2	*Swietenia macrophylla*	667.54[b]	766.01[b]
3	*Pericopsis mooniana*	1152.13[a]	1294.85[a]
4	*Tectona grandis*	841.00	959.00
CD for comparing species 1 and 2		318.25	343.25
CD for comparing species 1 and 2 with 3		366.33	395.11

Means column wise comparison
Values with same superscript do not differ significantly between themselves

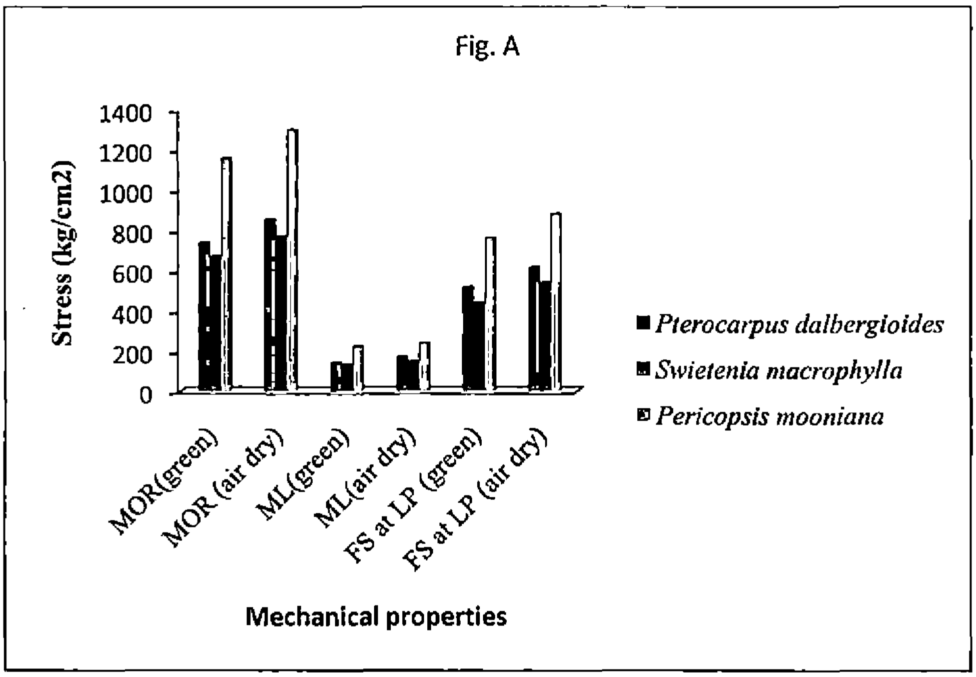
4.3.3.1b Modulus of rupture at air dry condition

Modulus of rupture at air dry condition was significantly (1%) different between the species studied (table 37). *Pericopsis mooniana* (1294.85) differed significantly for MOR at air dry condition and the values were found to be higher than teak (959) for MOR at air dry condition. *S. macrophylla* (766.01) and *P. dalbergioides* (849.81) showed similar values for MOR at dry condition. The latter two species showed lower value than that of teak with regard to the MOR at air dry condition.

4.3.3.2 Maximum load (ML) at green and dry condition

4.3.3.2a Maximum load at green condition

It was evident from one way anova (table 39) that maximum load was significantly different between the different tree species. Maximum load sustained by *Pericopsis mooniana* (220.89) was lower than the maximum load reported for teak (860) (Sekhar, 1988)



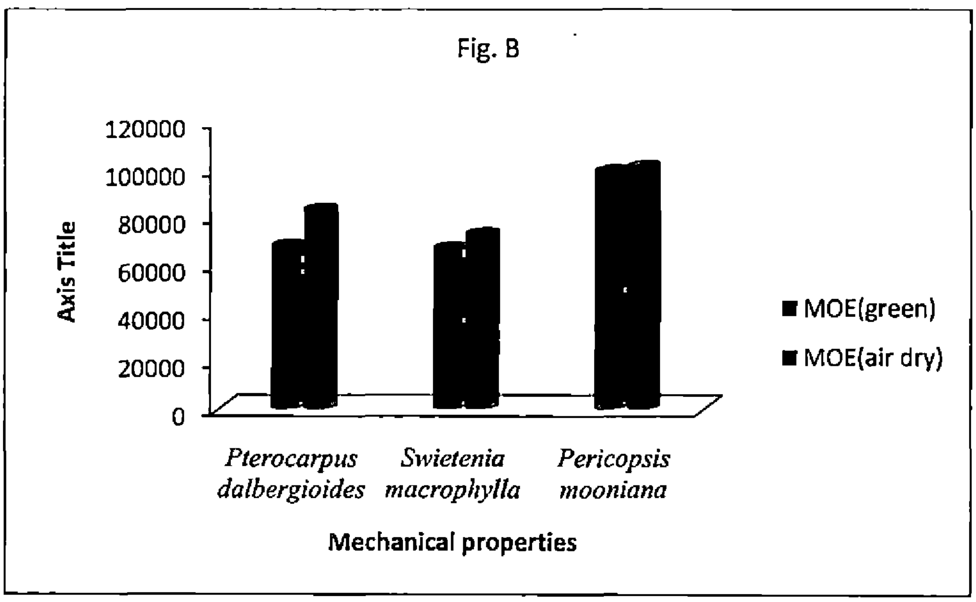


Fig 22. Comparison of static bending test between species

at green condition. These values were higher than that of *S. macrophylla* (129.48) and *P. dabergioids* (140.73), the latter two species being at par.

Table 39. Maximum load (ML) of P. *dalbergioides, S. macrophylla and Pericopsis mooniana* at green and dry condition

SI. No	Species	ML(kgcm^{-2})	
		Green	Air- dry
1	*Pterocarpus dalbergioides*	140.73^{b}	169.31^{b}
2	*Swietenia macrophylla*	129.48^{b}	144.79^{b}
3	*Pericopsis mooniana*	220.89^{a}	237.11^{a}
4	*Tectona grandis*	860.00	720.00
CD for comparing species1 and 2		60.13	63.79
CD for comparing species1 and 2 with 3		69.21	73.30

Means column wise comparison
Values with same superscript do not differ significantly between themselves

4.3.3.2b Maximum load at air dry condition

ML values at air dry condition were also found to be significantly different (1%) between species. ML values at the air dry condition in *Pericopsis mooniana* (237.11) was higher than the ML values at air dry condition of *P. dalbergioides* (169.31) and *S. macrophylla* (144.79) but was lower than that for teak (720). Later two species showed homogeneous ML values at air dry condition, but their values were lower than the ML value of teak at air dry condition.

4.3.3.3 Horizontal shear stress at maximum load (HS at ML) in green and air dry condition

4.3.3.3a Horizontal shear stress at maximum load in green condition

HS at ML value at green condition in *P.mooniana* (41.27) was found to significantly differ (table 40) from *S. macrophylla* (24.01) and *P. dalbergioides* (26.27). The latter two species showed homogeneous values for HS at ML at dry condition. However, HS at ML value was found to be higher in *P. mooniana.*

Table 40. Horizontal shear stress at maximum load (HS at ML) in *P. dalbergioides, S. macrophylla and Pericopsis mooniana* at green and air dry condition

SI. No	Species	HS at ML (kg/cm^2)	
		Green	Air dry
1	*Pterocarpus dalbergioides*	26.27^b	30.80^b
2	*Swietenia macrophylla*	24.01^b	27.32^b
3	*Pericopsis mooniana*	41.27^a	45.64^a
CD for comparing species 1 and 2		11.35	
CD for comparing species 1 and 2 with 3		13.06	

Means both row wise and column wise comparison
Values with same superscript do not differ significantly between themselves

4.3.3.3b Horizontal shear stress at maximum load in air dry condition

HS at ML at air dry condition in *P. mooniana* (45.64) was found to be significantly differ (1%) from *S. macrophylla* (27.32) and *P. dalbergioides* (30.80) (table 40), whereas the latter two species showed similar values for HS at ML at air dry condition. HS at ML value was found to be higher in *P. mooniana.*

4.3.3.4 Horizontal shear stress at limit of proportionality (HS at LP) in green and dry condition

4.3.3.4a Horizontal shear stress at limit of proportionality (HS at LP) in green condition

HS at LP values were found to be significantly different among the species studied (table 41). *P. mooniana* (27.13) differed significantly (1%) from *S. macrophylla* (15.72) and *P. dalbergioides* (18.40). The latter two species had values at par.

Table 41. Horizontal shear stress at limit of proportionality (HS at LP) of P. *dalbergioides, S. macrophylla and Pericopsis mooniana* at green and air dry condition

SI. No	Species	HS at LP (kg/cm^2)	
		Green	Air- dry
1	*Pterocarpus dalbergioides*	18.40^b	21.68^b
2	*Swietenia macrophylla*	15.72^b	19.09^b
3	*Pericopsis mooniana*	27.13^a	30.92^a
CD for comparing species 1 and 2		7.29	8.92
CD for comparing species 1 and 2 with 3		8.40	10.27

Means both row wise and column wise comparison
Values with same superscript do not differ significantly between themselves

4.3.3.4b Horizontal shear stress at limit of proportionality (HS LP) at air dry condition

Table 41 clearly illustrates the significant difference between species with respect to HS at LP in dry condition. *Pericopsis mooniana* (30.92) was found to have the highest value with respect to HS at LP at air dry condition. *S. macrophylla* (19.09) and *P. dalbergioides* (21.68) showed similar values for HS at LP at air dry condition.

4.3.3.5 Fibre stress at limit of proportionality (FS at LP) in green and air dry condition

4.3.3.5a Fibre stress at limit of proportionality (FS at LP) in green condition

FS at LP was found to be significant at five percent level (table 42) between the tree species under study. FS at LP values at green condition was higher in *P. mooniana* (758.69). *S. macrophylla* (437.78) and *P.dalbergioides* (513.88) was found to have similar values.

Table 42. Fibre stress at limit of proportionality (FS at LP) in *P. dalbergioides, S. macrophylla and Pericopsis mooniana* at green and air dry condition

Sl. No	Species	FS at LP (kg/cm^2)	
		Green	Air dry
1	*Pterocarpus dalbergioides*	513.88^b	612.34^b
2	*Swietenia macrophylla*	437.78^b	535.91^b
3	*Pericopsis mooniana*	758.69^a	877.68^a
4	*Tectona grandis* (taken as standard for comparison)		
CD for comparing species 1 and 2			
CD for comparing species 1 and 2 with 3			

Means column wise comparison
Values with same superscript do not differ significantly between themselves

4.3.3.5b Fibre stress at limit of proportionality (FS at LP) in air dry condition

FS at LP was found to be significant at one percent level (table 42) between the tree species under study. FS at LP values at air dry condition was higher in *P. mooniana* (758.69). *S. macrophylla* (437.78) and *P.dalbergioides* (513.88) was found to have similar values.

4.3.3.6 Modulus of elasticity at green and air dry condition

4.3.3.6a Modulus of elasticity (MOE) at green condition

Modulus of elasticity (MOE) at green condition was found to be significant (1%) between the different tree species under study (table 43).

P. mooniana (98996.23) showed highest values in comparison to *S. macrophylla* (66719.93) and *P. dalbergioides* (67738.05). *P. mooniana* was found to have lower value of

MOE at green condition when compared to teak (109700) as reported by Sekhar (1988). The latter two species were found to be similar with respect to modulus of elasticity at green condition. Both of them showed lower values as compared to teak.

Table 43. Modulus of elasticity (MOE) of P. *dalbergioides, S. macrophylla and Pericopsis mooniana* at green and air dry condition

Sl. No	Species	MOE ($kgcm^{-2}$)	
		Green	Air dry
1	*Pterocarpus dalbergioides*	67738.05 [b]	82771.39[b]
2	*Swietenia macrophylla*	66719.93[b]	72641.44[c]
3	*Pericopsis mooniana*	98996.23[a]	100778.03[a]
4	*Tectona grandis* (taken as standard for comparison)	109700.00	119600.00
CD for comparing species 1 and 2		2355.37	15658.04
CD for comparing species 1 and 2 with 3		27229.38	18023.75

Means column wise comparison
Values with same superscript do not differ significantly between themselves

4.3.3.6b Modulus of elasticity (MOE) at air dry condition

Modulus of elasticity among tree species was significant (1%) at air dry condition also. *P. mooniana* (100778.03) had the highest value compared to *S. macrophylla* (72641.44) and *P. dalbergioides* (82771.39) but was lower when compared to the MOE value of teak (119600) as reported by Sekhar (1988) at air dry condition. The latter two species were found to be homogeneous with respect to modulus of elasticity at air dry condition.

4.4 INTERRELATIONSHIP BETWEEN WOOD PROPERTIES

4.4.1 *Pterocarpus dalbergioides*

Table 44 shows the correlation coefficients between different wood properties in *P. dalbergioides*. From the table it can be seen that parenchyma percentage was negatively correlated with the horizontal shear stress at maximum load in air dry condition in static bending tests and positively correlated with crushing strength at limit of proportionality in compression strength perpendicular to grain at green condition. Compressive strength at 2.5 mm deflection at air dry condition in compression perpendicular to the grain test was negatively correlated with fibre percent and oven dry specific gravity. Crushing stress at limit of proportionality, crushing stress at maximum load and modulus of elasticity in compression parallel to grain test at green condition were found to be negatively correlated with fibre

Table. 44 Correlation analysis of different wood properties in *Pterocarpus dalbergioides*

	VA	VD	RH	RF	VL	FL	FWT	FLD	FD	RP	VP	PP	FP	SG
VA	1													
VD	0.95**	1												
RH	-0.20	-0.35	1											
RF	0.61*	0.605*	-0.54*	1										
VL	0.67**	.756**	-0.64*	.61*	1									
FL	0.31	0.43	-0.39	0.34	.61*	1								
FWT	0.04	0.07	-0.20	0.32	0	-0.06	1							
FLD	-0.30	-0.23	-0.18	-0.02	-0.18	-0.40	.78**	1						
FD	-0.26	-0.23	-0.19	-0.02	-0.22	-0.40	.80**	.975**	1					
RP	0.22	0.26	-0.16	0.28	0.45	0.25	-0.400	-0.46	-0.48	1				
VP	0.31	0.20	-0.01	0.18	0.12	0.00	.553*	0.20	0.32	-0.12	1.00			
PP	0.64*	0.422	0.07	0.43	0.15	-0.04	0.070	-0.28	-0.17	-0.21	0.48	1		
FP	-0.64**	-.52*	0.10	-.54*	-0.50	-0.19	0.190	.539*	0.45	-.69**	-0.39	-.54*	1	
SG	0.49	.57*	-0.25	0.43	.62*	.76**	-0.02	-0.29	-0.34	0.02	-0.03	0.19	-0.12	1

VA-vessel area, VD- vessel diameter, VF-vessel frequency, VL-vessel length, RH-Ray height, RW- ray width, RF- ray frequency, FWT- fibre wall thickness, FLD- fibre lumen diameter, FD- fibre diameter, RP- ray percent, VP- vessel percent, PP-parenchyma percent, FP- fibre percent

Table. 45 Correlation analysis of different wood properties in *Swietenia macrophylla*

	VA	VD	VF	RH	RW	RF	FWT	FLD	FD	RP	VP	PP	FP
VA	1.00												
VD	0.91**	1.00											
VF	-0.11	0.04	1.00										
RH	0.28	0.25	-0.28	1.00									
RW	0.65**	0.58*	-0.23	0.70**	1.00								
RF	-0.56*	-0.49	0.75**	-0.64*	-0.57*	1.00							
FWT	-0.12	-0.02	-0.17	0.15	-0.09	-0.15	1.00						
FLD	-0.29	-0.44	0.05	0.38	0.06	0.08	-0.13	1.00					
FD	-0.25	-0.34	0.06	0.29	-0.07	0.07	0.17	0.84**	1.00				
RP	0.38	0.29	-0.58*	0.10	0.27	-0.56*	-0.01	-0.44	-0.46	1.00			
VP	-0.61*	-0.43	0.17	0.04	-0.31	0.32	0.58*	0.24	0.51	-0.42	1.00		
PP	-0.14	-0.01	0.31	0.19	0.02	0.16	0.46	0.14	0.41	-0.63*	0.45	1.00	
FP	-0.16	-0.18	0.52*	-0.20	-0.21	0.52*	-0.45	0.41	0.21	-0.82**	-0.05	0.14	1.00

VA-vessel area, VD- vessel diameter, VF-vessel frequency, VL-vessel length, RH-Ray height, RW- ray width, RF- ray frequency, FWT- fibre wall thickness, FLD- fibre lumen diameter, FD- fibre diameter, RP- ray percent, VP- vessel percent, PP-parenchyma percent, FP- fibre percent

Table. 46 Correlation analysis of different wood properties in *Pericopsis mooniana*

	VA	VD	RH	FL	FWT	FLD	FD	RP	PP	FP	SG
VA	1.00										
VD	0.86**	1.00									
RH	-0.73*	-0.67*	1.00								
RW	0.35	0.53	-0.27								
FL	-0.50	-0.33	0.17	1.00							
FWT	0.26	0.34	-0.25	0.07	1.00						
FLM	0.41	0.25	-0.16	-.71*	0.26	1.00					
FD	0.35	0.15	-0.12	-0.51	0.53	0.89**	1.00				
RP	0.62	0.71*	-0.10	-0.47	0.54	0.52	0.53	1.00			
PP	0.41	0.60	-.70*	-0.16	0.08	0.19	0.09	0.17	1.00		
FP	-0.64	-0.84**	0.53	0.40	-0.33	-0.44	-0.35	-0.71*	-0.81**	1.00	
SG	0.57	0.60	-0.45	-0.09	0.85**	0.33	0.50	0.61	0.09	-0.37	1.00

VA-vessel area, VD- vessel diameter, VF-vessel frequency, VL-vessel length, RH-Ray height, RW- ray width, RF- ray frequency, FWT- fibre wall thickness, FLD- fibre lumen diameter, FD- fibre diameter, RP- ray percent, VP- vessel percent, PP-parenchyma percent, FP- fibre percent

Table. 47 Correlation analysis of different wood properties in *Pterocarpus dalbergioides*

	Compression perpendicular to grain					Compression parallel to grain			Static bending test					
	CS at LP(g)	CS at LP(d)	CS at 2.5mm(g)	CS at 2.5mm(d)	MOE(g)	CS at LP(g)	CS at ML(g)	MOE(g)	MOR(d)	ML(d)	HS at ML(d)	HS at LP(d)	FS at LP(d)	MOE(d)
VA	0.751	0.421	0.806	0.496	0.731	0.628	0.765	0.747	.964**	.899*	-0.658	.907*	0.713	0.87
FL	-0.805	-0.288	-0.779	-0.325	-0.844	-.967**	-.944*	-.946*	-0.646	-0.725	.907*	0.142	-.910*	-0.767
FWT	-0.722	-0.363	-0.77	-0.445	-0.723	-0.199	-0.381	-0.322	-0.62	-0.694	0.501	.990**	-0.481	-0.732
FLD	-0.625	-0.7	-0.624	-0.744	-0.495	-0.069	-0.167	-0.13	-0.521	-0.607	0.446	.893*	-0.411	-0.598
PP	.965**	0.71	.948*	0.76	.886*	0.863	.892*	.886*	.929*	.978**	-.966**	-0.553	.976**	.968**
FP	-0.821	-.910*	-0.791	-.940*	-0.648	-0.656	-0.66	-0.667	-0.877	-.895*	0.811	0.548	-0.824	-0.837

Table. 48 Correlation analysis of different wood properties in *Swietenia macrophylla*

	Compression parallel to grain			Static bending test			
	ML(d)	MOE(g)	MOE(d)	MOR(d)	ML(g)	ML(d)	HS at ML(g)
VD	0.458	.927*	-0.137	-0.137	-.914*	-0.011	0.162
RF	-0.495	-0.031	-0.573	-0.571	-0.088	-.896*	0.458
RP	0.062	-0.277	0.03	0.03	0.213	0.049	-.954*
FP	-0.741	-0.453	-0.554	-0.552	0.319	-.939*	0.415
SG(O)	.930*	0.329	.914*	.914*	-0.095	0.698	-0.147

Table. 49. Correlation analysis of different wood properties in *Pericopsis mooniana*

	Compression perpendicular to grain					Compression parallel to grain			Static bending test						
	CS at LP(g)	CS at LP(d)	CS at 2.5mm(g)	CS at 2.5mm(d)	MOE(d)	CS at ML(d)	MOE(g)	MOE(d)	MOR(g)	MOR(d)	ML(g)	HS at ML(g)	HS at LP(g)	FS at LP(g)	MOE(d)
VA	0.9	0.824	0.892	0.841	0.908	0.318	0.81	0.532	0.878	0.906	0.853	0.87	0.85	0.854	0.63
VD	0.865	0.931	0.873	0.919	0.856	0.964	0.939	.999*	0.095	0.157	0.045	0.078	0.039	0.047	-0.292
VF	-0.328	-0.466	-0.343	-0.439	-0.31	-0.904	-0.487	-0.779	0.578	0.526	0.618	0.591	0.623	0.617	0.845
RH	-1.000**	-0.988	-1.000*	-0.993	-1.000*	-0.699	-0.984	-0.847	-0.584	-0.633	-0.542	-0.57	-0.537	-0.544	-0.23
RW	0.877	0.939	0.884	0.928	0.868	0.957	0.947	.998*	0.118	0.18	0.069	0.102	0.063	0.07	-0.269
RF	0.831	0.738	0.822	0.759	0.841	0.185	0.722	0.41	0.936	0.956	0.917	0.93	0.914	0.918	0.73
VL	0.731	0.825	0.742	0.807	0.718	.999*	0.839	0.982	-0.13	-0.068	-0.179	-0.147	-0.185	-0.178	-0.498
FL	-0.268	-0.12	-0.252	-0.151	-0.285	0.5	-0.096	0.284	-0.94	-0.916	-0.955	-0.945	-0.957	-0.955	-.999*
FWT	0.195	0.339	0.21	0.31	0.176	0.836	0.362	0.685	-0.685	-0.638	-0.72	-0.697	-0.725	-0.719	-0.911
FLD	0.569	0.44	0.556	0.467	0.584	-0.188	0.418	0.047	1.000**	.997*	.999*	1.000**	.999*	.999*	0.93
FD	0.474	0.336	0.459	0.365	0.49	-0.297	0.313	-0.065	0.992	0.982	.997*	0.994	.997*	0.997	0.965
RP	0.876	0.939	0.884	0.928	0.867	0.958	0.947	.998*	0.118	0.179	0.068	0.101	0.062	0.07	-0.27
VP	-0.563	-0.68	-0.576	-0.657	-0.547	-0.984	-0.698	-0.915	0.345	0.286	0.392	0.361	0.397	0.39	0.677
PR	0.997	.997*	.998*	.999*	0.995	0.755	0.995	0.888	0.515	0.567	0.471	0.5	0.466	0.473	0.149
FP	-0.99	-1.000**	-0.992	-1.000*	-0.987	-0.794	-.999*	-0.914	-0.461	-0.515	-0.416	-0.446	-0.41	-0.417	-0.087
SG(O)	0.630	0.739	0.642	0.718	0.615	0.996	0.755	0.946	-0.266	-0.205	-0.314	-0.282	-0.320	-0.312	-0.614

length. In the case of static bending test at air dry condition, horizontal shear stress at limit of proportionality was negatively correlated with the fibre length whereas it was found to be positively correlated with the horizontal shear stress at maximum load. In the same test at dry condition, modulus of rupture and maximum load were found to be positively correlated with vessel area. Correlation of specific gravity with anatomical characters shows that vessel diameter, vessel length and fibre length are significantly correlated with specific characters. Many of the anatomical properties were also found to be significantly correlated each other (table 45).

4.4.2 *Swietenia macrophylla*

Results of correlation analysis are illustrated in table 45. Vessel diameter was positively correlated with the horizontal shear stress at maximum load, whereas it was found to be negatively correlated with fibre stress at limit of proportionality at dry condition in static bending test. It was noticed that oven dry specific gravity showed positive correlation with CS at ML in compression parallel to grain at dry condition. With respect to static bending test, oven dry specific gravity was found to be positively correlated with HS at LP and FS at LP in green condition. Fibre percent showed negative correlation with MOE at green condition in the static bending test. In the case of *S. macrophylla*, none of the anatomical characters were correlated with specific gravity. Correlation between anatomical properties was given in table 46.

4.4.3 *Pericopsis mooniana*

Correlation analyses conducted to study the relationship between different wood properties in P. mooniana are presented in table 46. Ray height was found to have negative correlations with CS at LP and CS at 2.5 mm deflection at green condition and modulus of elasticity at dry condition in compression perpendicular to grain test. Vessel diameter and ray width were found to have positive correlation with modulus of elasticity at dry condition in compression parallel to grain. Vessel length showed significant correlation with CS at ML at dry condition in compression parallel to grain. It was noticed that fibre lumen diameter was positively correlated with MOR (green and air dry condition), ML (green condition), HS at ML (green condition) and HS at LP (green condition). Fibre length showed positive correlation with MOE (air dry condition) in the static bending test. In the case of *P. mooniana* wall thickness was correlated with specific gravity. Most of the anatomical properties were found to be correlated each other .

Even though almost all the wood properties were found to have significant correlation with each other in *P. mooniana*, reliability of the correlation is questionable. Because of the limited availability of replicates in terms of number of trees, data pertaining to different wood properties were lower than the minimum and could not be selected for the regression analysis.

4.5 REGRESSION ANALYSIS

4.5.1 Dependences of specific gravity on anatomical properties

Linear and quadratic models were developed to show the dependence of specific gravity on anatomical properties. Table 50 illustrates the regression equation developed to show the dependence of specific gravity on various anatomical properties in species viz., *Pterocarpus dalbergioides, S. macrophylla and P.mooniana.*

Table 50. Results of regression in the case of specific gravity (Y) with anatomical characters

Species	Independent variable (X)	Name of fitted equation	Fitted equation	R^2square
P. dalbergioides	Vessel diameter	Quadratic	$Y = -1.028 + 0.014X - 0.000026X^2$	0.579
	Vessel length	Linear	$Y = 0.123 + 0.004X$	0.389
	Fibre length	Linear	$Y = 0.053 + 0.001X$	0.569
S. macrophylla	No correlation exists			
P. mooniana	Wall thickness	Linear	$Y = 0.675 + 0.120X$	0.720

From table 48 it can be seen that regression equation was developed by taking specific gravity as dependent variable (Y) and anatomical properties as independent variables(X). In the case of *P. dalbergioides* correlation of specific gravity with vessel diameter was depicted through a quadratic equation whereas correlation of specific gravity with vessel length and fibre length were given through linear equation. No correlation was observed in *S. macrophylla* in the specific gravity-anatomical property relationships.

4.5.2 Dependences of mechanical properties on anatomical properties in *Pterocarpus dalbergioides*

In the case of *P. dalbergioides* linear models were developed to show the relationship between mechanical properties and anatomical properties. Results of regression analysis in *P. dalbergioides* were presented in table 51. Regression equation was developed by considering mechanical properties as dependent variables (Y) and anatomical properties as independent variables (X). Regression model revealed that mechanical properties related with anatomical properties linearly.

Table 51. Regression equations showing the relationship between mechanical properties and anatomical properties in *P. dalbergioides*

Dependent variable (Y)	Independent variable (X)	Name of fitted equation	Fitted equation	R^2square
CMPR_CS at LP (G)	Parenchyma percent	Linear	Y = -5.711 + 6.364 X	0.931
CMPR_CS at LP (D)	Fibre percent	Linear	Y = -427.016 - 88.528 X	0.829
CMPR_CS at 2.5mm (G)	Parenchyma percent	Linear	Y = -19.776 + 10.111 X	0.948
CMPR_CS at 2.5 mm (D)	Fibre percent	Linear	Y = 681.066 – 8.538 X	0.883
CMPR_MOE(G)	Parenchyma percent	Linear	Y = 34.699 + 369.598 X	0.785
CMPL_CS at LP (G)	Fibre length	Linear	Y = 1140.877 - 0.856 X	0.935
CMPL_CS at ML(G)	Fibre length	Linear	Y = 1250.767 - 0.885 X	0.891
CMPL_CS at ML(G)	Parenchyma percent	Linear	Y = 89.797 + 21.673 X	0.795
CMPL_MOE (G)	Fibre length	Linear	Y = 65355.308 – 45.895 X	0.894
CMPL_MOE (G)	Parenchyma percent	Linear	Y = 5244.479 + 1115.490 X	0.785
STBD_MOR(D)	Vessel area	Linear	Y = -533.584 + 0.024 X	0.930
STBD_MOR(D)	Parenchyma percent	Linear	Y = 16.482 + 60.765 X	0.863
STBD_ML(D)	Vessel area	Linear	Y = -73.781 +0.004 X	0.808
STBD_ML(D)	Parenchyma percent	Linear	Y = 1.317 + 11.672 X	0.957
STBD_ML(D)	Fibre percent	Linear	Y = 811.114 – 10.464 X	0.801
STBD_HS at ML(D)	Fibre length	Linear	Y = -2633.801 + 2.808 X	0.822
STBD_HS at ML(D)	Parenchyma percent	Linear	Y = 1307.124 - 80.330 X	0.933
STBD_HS at LP(D)	Fibre wall thickness	Linear	Y = 10.833 – 15.654 X	0.981
STBD_HS at LP(D)	Fibre lumen diameter	Linear	Y = -108.642 – 8.707 X	0.797
STBD_FS at LP(D)	Fibre length	Linear	Y = 4732.333 – 4.376 X	0.828
STBD_FS at LP(D)	Parenchyma percent	Linear	Y = -1209.719 + 121.726 X	0.953
MOE(D)	Parenchyma percent	Linear	Y = -131.403 + 4251.444 X	0.938

CMPR-compression perpendicular to grain; CMPL- compression parallel to grain; STBD- static bending test; CS at LP-Compressive stress at limit of proportionality; CS at 2.5 mm- compressive stress at 2.5 mm deflection; MOE- modulus of elasticity; MOR- Modulus of rupture; FS at LP- Fibre stress at limit of proportionality; HS at LP- Horizontal shear stress at limit of proportionality; ML-maximum load

4.5.2 Dependence of mechanical properties on anatomical properties in *Swietenia macrophylla*

Regression equation showing the relationship between mechanical and anatomical properties is presented in table 51 and 52. Among the three species studied *S. macrophylla* showed least correlation between mechanical and anatomical properties.

Table 52. Regression equations showing the relationship between mechanical properties and anatomical properties in *Swietenia macrophylla*

Dependent variable	Independent variable (X)	Name of fitted equation	Fitted equation	R^2
CMPL_CS at ML(D)	Specific gravity	Linear	Y = -672.005 + 2084.857 X	0.864
STBD_HS at ML(D)	Vessel diameter	Linear	Y = -2357.052 + 16.570 X	0.859
STBD_HS at LP(G)	Specific gravity	Linear	Y = -13.169 + 55.172 X	0.835
STBD_FS at LP(G)	Specific gravity	Linear	Y = -379.750 + 1561.336 X	0.836
STBD_FS at LP(D)	Vessel diameter	Linear	Y = 3351.520 – 19.144 X	0.835
MOE(g)	Ray frequency	Linear	Y = 97608.613 – 3776.214 X	0.802
MOE(g)	Ray frequency	Linear	Y = 103689.910 – 1055.14 X	0.881
MOE(D)	Ray %	Linear	Y = 72821.723 – 667.261 X	0.911

Discussion

DISCUSSION

Fast growing and high yielding plantations are being raised all over the country under various afforestation and reforestation programmes to cater to the growing demands for pulp, paper and various solid wood products. However various native and exotic species being grown under such programmes are often associated with limited knowledge on their wood properties and its variation.

Generally wood physical, anatomical and mechanical properties of a timber species determine its quality. Therefore, wood quality evaluation is a prerequisite for the establishment of commercial plantations having high potential for various end uses. However, a major drawback for the promotion, management and efficient utilization of new timber species such as *P. mooniana* and *P. dalbergioides* which are covered under this study is the lack of information regarding their wood properties and wood quality when grown under the prevailing eco-climatic conditions in different localities with in this country. Availability of such information prior to large scale forest plantation establishment plays a crucial role in selecting the species most appropriate for the envisaged end use. Even for popular timber species such as S. *macrophylla*, covered under this trial also wood property information when grown under local conditions is rare in the literature (Amarasekera, 1996).

Considering the increasing demand for new species from fast grown plantations as alternative timber for various end uses and also for generating database of the various wood properties of different plantation grown species for establishing quality plantations with improved wood stocks, a study was conducted to evaluate and compare the different wood properties of three plantation grown tree species grown in the research trials of Kerala forest department in various part of the state.

Data generated on the various physical, anatomical and mechanical properties of three plantation grown species viz., *Pterocarpus dalbergioides, Swietenia macrophylla* and *Pericopsis mooniana* are discussed hereunder.

5.1 PHYSICAL PROPERTIES

Wood properties vary greatly within a tree. Wood property variation patterns that arise from apical or cambial aging and positional effects of the crown are regarded as intrinsic. External factors such as environment, site conditions and silvicultural treatments also have impacts on regular patterns of wood variation and these are regarded as extrinsic. Wood properties vary within the position in a tree and with the age at which the growth sheath is formed. Therefore, systematic radial and axial patterns of wood property variations can be identified (Amarasekera and Denne, 2002).

5.1.1 Specific gravity

Specific gravity may be the most widely studied property of wood. Specific gravity is a function of the proportion of cell wall materials versus cellular voids. Many authors identify specific gravity as a key wood property in forest products because it has a major effect on the yield and quality of both fibrous and solid wood products (Bhat, 1985; Haslett and Young, 1990). As such, specific gravity is often considered as a measure of wood quality (Zobel and van Buitjenen, 1989; Woodcock and Shier, 2002). Numerous authors have classified timber species based on specific gravity as it is the single best index that can be easily measured to predict strength properties of wood (Bhat, 1985; Amarasekera, 1996).

The present study revealed that wood specific gravity differed significantly between species and between radial positions within species. Except specific gravity at green condition, air dry and oven dry specific gravity showed significant difference between tree species and within species. Compared to *S. macrophylla* and *P. dalbergioides*, *P. mooniana* showed high specific gravity in the fresh, air dry and oven dry conditions. *S. macrophylla* and *P. dalbergioides* were found to be homogeneous with each other with regard to specific gravity.

In the case of *P. mooniana* there was an increasing trend in oven dry specific gravity from pith towards the periphery position and the mean value reported for air dry specific gravity was 0.73. Ishiguri et al. (2011) noticed that specific gravity at the bark side was higher than the pith side for *P. mooniana* plantations grown in Indonesia and reported an average value of 0.85 for specific gravity. Increase in oven dry specific gravity in the pith and periphery region may be associated with increase in vessel frequency, fibre wall thickness and fibre lumen diameter. For the genus Eucalyptus, the most common trend found for basic density is an increase radially from pith to bark and axially from the base to apex (Ferreira, 1972; Wilkes, 1988; Valente et al., 1992) which is in tune with the pattern of radial variation in specific gravity found in ***P. mooniana***. Even though *P. mooniana* showed a decrease in trend towards the middle from the pith, it further showed a increase towards the bark region. However, an increase in specific gravity for *P. mooniana* in the green condition may attributed to the highest species averages in moisture content at the green stage compared to *S. macrophylla* and *P. dalbergioides*.

Differences in basic density can be seen between species, sites, trees and within the tree. Density variation generally occurs as a function of growth rate, climate, silviculture and breeding. Generally it tends to increase from the centre of the tree to the bark. In the case of *S. macrophylla* and *P. dalbergioiges*, oven dry specific gravity was found to increase towards middle from the pith and periphery region. Perera (2008) revealed that *S. macrophylla* exhibited a slight increase in specific gravity from pith to bark and growth rates represented by ring width showed poor correlations with specific gravity in *S. macrophylla*. Lin et al. (2012) also observed a gradual increase in specific gravity from pith outwards in plantation grown *S. macrophylla* Both results were slightly contradictory to the present study in which a slight increase was observed toward the middle region from the pith, again showing a declining trend toward periphery. Variation in the pattern of change in wood density for the latter two species may be attributed to the variation in the components that comprise wood which may include changes in vessel size and frequency, fibre dimensions (wall thickness and diameter), percentages of parenchyma (ray) and wood chemistry.

Trees having lower mean basic density had thinner fibre walls and wider vessel lumens than higher mean density trees. Therefore, higher oven dry specific gravity of *P. mooniana* may be attributed to its lower species averages for vessel diameter and vessel area. It may also be due to high vessel frequency. Lower specific gravity of *P. dalbergioides* and *S. macrophylla* may be attributed to their high values of vessel area and vessel diameter. However, differences in density did not seem to be consistently related to proportion of vessels, fibres and rays, though each of those parameters varied significantly between species.

There are two different groups of hardwoods, namely ring-porous and diffuse-porous. Wood of these groups is affected differently by growth rate. Fukazawa (1983) stated that in the ring-porous hardwoods changes of basic density are influenced by the ring widths, while those of diffuse porous hardwoods are almost independent of the ring width. The three species that are discussed mainly in this research work, *Pterocarpous dalbergioides*, *Swietenia macrophylla* and *Pericopsis mooniana* are diffuse porous hardwoods. Many researchers are in agreement with the fact that fast growth in ring porous hardwoods results in dense wood (Zobel and van Buijtenen, 1989), while in diffuse porous hardwoods, growth rate differences have little effect on specific gravity (Ferreira, 1968; Skolman, 1972; Perera and Amarasekera, 2003; Jayewardenena and Amarasekera, 2008).

Briscoe et al. (1963) reported an increase in specific gravity of *S. macrophylla* with increased growth rates while Chudnoff and Geary (1973) found no significant relationship between tree size (representing the growth rate) and wood specific gravity. Analyzing ring characteristics of 30 year old *S. macrophylla*, Lin et al. (2012) further concluded that it is unlikely for growth rates of plantation grown mahogany trees to have a significant impact on wood specific gravity. It was observed that specific gravity shows a poor correlation with growth rate measured by ring width. Hence it is unlikely that wood specific gravity of these species can be changed by influencing growth rate.

Two samples of similar density may have markedly different fibre properties. Patterns of variation of the components defining density may be different from that of density itself. For example, points within a stem where fibre have a small diameter and thin walls may have similar density to other points where fibres have a larger diameter and thicker walls.

Wood basic density is considered one of the most important features in genetic improvement programmes (Zobel and Talbert, 1988) and is one of the most often studied wood quality traits (Downes et al., 1997; Peszlen, 1998). It is a complex feature influenced by cell wall thickness, the proportion of the different kind of tissues, and the percentages of lignin, cellulose and extractives (Valente et al., 1992). Site influence was significant for basic density, which ranged from 0.364 kg/m3 to 0.455 kg/m^3.

Density may vary among trees of the same species due to genetics and ecological differences, as well as within a tree, i.e., age-related longitudinal and radial variation (Wilkes, 1984; Fukazawa, 1984; Wilkins, 1991; Wate et al., 1999). Wood density results from different interacting factors, mostly anatomical, such as fibre diameter, wall thickness and pro-portion of non-fibrous cell types, and also chemical such as ash and extractives content (Fujiwara, 1992; Sandercock et al., 1995).

5.1.2 Moisture content

Moisture content at green condition was higher in *P. mooniana*, followed by *S. macrophylla* and *Pterocarpus dalblbergioides*. Species averages were found to differ significantly differed with regard to the moisture content at green condition only. At air dry condition both radial variation as well as species averages were found to be non significant. There was no definite pattern of change in moisture content along the radial position in *P. dalbergioides* and *P.mooniana* at green condition. *S. macrophylla* showed increasing moisture content towards periphery. At air dry condition both *S. macrophylla* and *P. mooniana* found to have increasing moisture content towards periphery from pith position. Increased moisture content during air dry condition may be associated with large vessel area and vessel lumen diameter in those species.

5.1.3 Shrinkage

Dimensional changes in wood occurring with changing atmospheric conditions is one of its most undesirable characteristics, since it adversely affects the use of wood in many situations. Dimensional movement in wood is basically manifested by water absorption, but is attributable to a number of other factors related to its physical, chemical nature and anatomical structure.

The present investigation on shrinkage properties in species viz., *P. dalbergioides, S. macrophylla and P. mooniana* showed that species averages as well as radial variation within species were non - significant with respect to radial shrinkage at green condition. Species averages were found to be significantly different at air dry and oven dry condition. *P. mooniana* showed highest radial as well as tangential shrinkage in all the three conditions. *S. macrophylla* and *P. dalbergioides* showed homogeneous values for radial and tangential shrinkage. This may be associated with a higher vessel frequency observed in *P.mooniana.*

Generally tangential shrinkage was higher than radial shrinkage for all the three species studied in three different conditions. Although no significant radial pattern of change was observed in all the three species under study *P. mooniana* showed a decreasing tangential shrinkage towards periphery. Similar studies by Shanavas and Kumar (2006) showed that *Acacia mangium* had a decreasing tangential shrinkage towards periphery. Species averages in radial and tangential shrinkage for *P. dalbergioides* were 2.78percent and 4.14 percent respectively. Values were lower compared to natural grown *P. dalbergioides* values for radial (3.3percent) and tangential (4.4percent) shrinkages reported by Limaye (1933). When compared to 22 year old plantation grown *P. dalbergioides*, radial shrinkage (2.94percent) was lower, where as tangential shrinkage (4.03percent) showed a little increase. Entire value for radial shrinkage was higher for three species under study in the oven dry condition when compared to the corresponding radial shrinkage values of (2.3percent) teak as reported by Sekhar (1988).

The present study revealed values of shrinkage in *S. macrophylla* from 3.58 % (radial shrinkage) to 4.63percent (tangential shrinkage) at oven dry condition. Jara et al. (2008) reported that *S. macrophylla* had radial shrinkage values that ranged between 2.52percent to 2.70percent tangential shrinkage range from 3.24percent to 3.69percent. These reported values were lower than the values from the present study. This is expected since wood shrinks and swells more along the tangential direction compared to the radial direction.

Mahogany wood is well known for its ability to remain dimensionally stable in use when properly dried. This is due to its low shrinkage to swelling properties and smaller ratio of radial to tangential shrinkage. Also, mahogany from the West Indies and South America has good dimensional stability and is somewhat superior in this respect to the Central American mahogany, when exposed to different relative humidities. Its dimensional stability and good finishing qualities make it a premium material for the construction of high value furniture and interior fittings (Rocafort, 1973).

The anisotropicity in shrinkage behaviour of wood is attributed to the microscopic orientation of the various cells, their distribution and alignment as well as the differences at ultrastructural level. In the longitudinal direction (along the grain) the changes are the least and range between 0.1 to 0.2 percent only. This is mainly due to the orientation of the microfibrils in the cells which run almost parallel to the axis. Dimensional changes in the two transverse planes are much higher and range between 4.3 to 14 percent in the tangential 2.1 to 8.5 in the radial direction respectively (Kumar, 1998).

The anisotropy on the transverse face of the wood relates to the difference in the shrinkage ratio in the tangential and radial directions. There are greater numbers of factors contributing to anisotropy in the transverse face in comparison with the longitudinal face. For example, 1) the interaction of early wood and the latewood (Pentoney, 1953), 2) the effect of rays (McIntosh, 1957), and 3) differences in microfibril angle (Barber and Meylan, 1964) or 4) lignifications (Boyd, 1974) between radial wall and tangential wall in tracheids. Thus, the anisotropy in the transverse plane is a result of a complex interplay of these factors.

The swelling or shrinkage of wood shows anisotropy and the ratio is generally 10 (tangential): 5 (radial): 0.1–1 (longitudinal). Considerable dimensional changes that occur due to swelling or shrinkage are the cause of cracks in lumber and internal stresses and are undesirable characteristics from the point of view of timber utilization (Sakagami et al., 2007). On the other hand, swelling and shrinkage could also be considered as 'intelligent' characteristics of wood because wood can change dimensions by itself in response to the atmosphere (Okuma, 1998).

Since chemical nature of the wood substance in all the wood species is more or less are the same, differences in dimensional changes in different wood species are grossly attributed to differences in density and hygroscopicity. Dimensional changes are proportional to the volumetric changes in the water held in the cell wall, wood species having higher wood content thus absorb more water and hence display a higher dimensional movement.

5.1.4 Heartwood percentage and sawn wood recovery

Analysis of heartwood- sapwood ratio showed that species differences were significant among the three species studied. *S. macrophylla* showed highest value with regard to the heartwood percent followed by *Pericopsis mooniana* and *P. dalbergioides*. Higher heartwood percentages in *S. macrophylla* and *P. mooniana* may be attributed to their ages. Plantations of

S. macrophylla and *P.mooniana* were established in 1924 and 1928 respectively, whereas plantations of *Pterocarpus dalbergioides* was establishes in 1954. Perez et al. (2003) reported increase of heartwood content in some fast growing tropical species with increase in age.

A positive variation of sapwood area with radial growth has been shown for *Eucalyptus globulus* trees in various conditions, i.e. at different plant densities (Gominho and Pereira, 2005), in trees grown at different sites (Miranda et al., 2007), and in fertilised and irrigated trees (Miranda et al., 2006). Miranda et al. (2009) suggested that in 18 year old *E. globulus* spacing impacts tree dimensions and therefore heartwood quantity. Trees grown with lower plant densities will have more heartwood than those grown with higher plant densities and the balance of sapwood and heartwood production on a unit area basis should be considered when planning initial spacing.

Miranda et al. (2006) reported high values of heartwood proportion at breast height viz., between 68 and 78 percent for 18 year old *E. globulus* trees, and data are also available for younger *E. globulus* trees: 43percent in 9 year old (Gominho and Pereira, 2000), and 29 – 6 percent in 8-year old trees (Miranda et al., 2007). However, these studies indicated that it is not age but tree dimensions, particularly tree diameters that are the main factors responsible for heartwood development.

Variation of sapwood width within species may be attributed to factors such as site (Nelson, 1976), climate (Chalk, 1951), elevation (Lassen and Okkonen, 1969) and tree vigour (Wellwood and Jurazs, 1968). 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; Higgins, 1984; Wilkins, 1991). Heartwood development is linked to tree size, and even aged trees that grow more in diameter and height have more heartwood and a higher heartwood proportion in the stem (Gominho and Pereira, 2000, 2005; Gominho et al., 2001; Miranda et al., 2006).

Sawn wood recovery rate showed a trend wherein was found to be higher in *P. mooniana* was having a higher value followed by *P. dalbergioides* and *S. macrophylla* whereas, log volume was found to be higher in *S. macrophylla*. Both log volume and sawn wood recovery may be related with the age of the plantation. Moreover, log volume depends on its diameter and length of the log whereas sawn wood recovery rate varies with the form, crookedness as well as diameter of the log. Since *S. macrophylla* plantation was more than 85 years old it was expected to yield a higher log volume. Even though *P. mooniana* plantation trees were well past its rotation age, growth rate was found to be very low due to unfavourable conditions. Hence, log volume in *P. mooniana* was lower than *P.dalbergioides* whose plantation was established only in 1954.

5.2 ANATOMICAL PROPERTIES

5.2.1 Vessel morphology

Species averages of vessel area and vessel diameter were highest in *P. dalbergioides* followed by *S. macrophylla* and *P. mooniana*. Both radial variation within species as well as between species variation were found to be significant. All the species under study showed an increasing trend in vessel area and vessel diameter towards periphery from the pith region. Vessel frequency showed a reverse trend in species averages, in which *P. mooniana* (5.58) showed highest value followed by *S. macrophylla* and *P. dalbergioides*. Ishiguru et al. (2011) reported a value of 11.1/mm^2 for vessel frequency. This study also found a similar radial increase of vessel diameter towards the periphery in comparison to the present study. Ogata et al. (2008) reported the values for vessel diameter and vessel frequency in *P. mooniana* as 160–170 µm, 8–

10 vessels/mm^2. Present study showed a value of 128.7 μm and 6 vessels/mm^2 respectively for the above character.

There was no significant radial variation in vessel frequency with in species. However, vessel frequency first showed a decreasing trend from pith towards middle, thereafter increasing towards periphery. Vessel length was found to be highest in *P. mooniana* followed by *P. dalbergioides* and *S. macrophylla*, the former mentioned two species not differing significantly. Regarding radial variation in vessel length, no specific pattern of change was observed.

Vessel morphology is substantially influenced by environment. Studies by Carlquist (1966) and Zhang et al. (1988) have shown that that vessel diameter and vessel element length decreased with increasing aridity and that vessel numbers increase. This view is supported by the work of Tyree et al. (1994) which showed that, while vessel efficiency increases with vessel diameter, safety of the transpiration system increases with decrease in vessel diameter and increase in vessel numbers. A study by Wilson et al. (1997) showed significant and consistent variability of vessel morphology and distribution within a ring and from pith to bark in a 7-year-old *Eucalyptus globulus*.

In a study of 30 year old *E. pilularis*, Bamber and Curtin (1974) showed that, while vessel diameter increased with age, vessel frequency decreased. Despite the decrease in vessel frequency, vessel area increased from 7.9 % in ring 1 to 11.9 % in ring 30. In a study of 8 .5 year old *E. nitens* Mc Kimm and Ilic (1987) showed vessel frequency initially decreased with increasing distance from the pith before becoming constant. The same study showed that vessel radial and tangential diameter rapidly increased with increasing distance from pith. All these reports conformed the present result for vessel diameter and partially for vessel frequency.

5.2.2 Fibre and ray morphology

Wood properties such as fibre and ray characteristics are used to evaluate the suitability of a wood for a particular application. Differences in fibre and ray properties are observed between species, sites, trees and within the tree. Fibre dimensions are determined by the dimensions of the cambial fusiform cells from which they are derived and by processes that occur during cell differentiation (Ridoutt and Sands, 1993, 1994). The length variation in phloem fibres also has been considered as a combined effect of intrusive growth and of the changes in fusiform cells associated with the aging of the cambium (Ghouse and Siddiqui, 1976)

Ray height and ray width were found to be higher in *S. macrophylla* followed by *P. mooniana* and *P. dalbergioides*. No definite pattern of radial variation was found with regard to ray height and ray width. Ray frequency was higher in *P. dalbergioides*, followed by *P. mooniana* and *S. macrophylla*. The latter two species were found to be homogeneous. Except fibre lumen diameter, species averages in all other fibre characteristics were found to be homogeneous. Fibre length showed an increasing trend towards periphery from pith position in *P. dalbergioides*. *S. macrophylla* first showed an increasing trend toward periphery, even though *S. macrophylla* showed a slight level off towards the middle region. Both of them showed an increase in fibre wall thickness towards middle from pith and then showed a decreasing trend towards periphery.

Butterfield et al. (1993) on *Hyeronima alchorneoides* and *Vochysia guatemalensis* also recorded an increase in fibre length radially. Fibre length increased radially from pith to bark, but axial variation was less consistent in the case of *Eucalyptus globulus* (Raymond and Muneri, 2001). Increasing trend in fibre length from pith to periphery at all height levels for *E. globulus* was reported by Jorge et al. (2000). Ismail et al. (1995) reported that in *Neolamarchia cadamba*, fibre length and fibre wall thickness increased from pith to bark while fibre diameter and fibre lumen diameter were found to first increase and then decrease towards the bark. *P. mooniana* in the case of radial variation in fibre diameter and *S. macrophylla* for fibre lumen diameter showed the same trend given by Ismail et al. (1995) in *Neolamarchia cadamba*.

The increase in fibre length and fibre wall thickness is associated with the normal transition from juvenile to mature wood (Bendtsen, 1978). Bhat et al. (1989) studied fibre length variation in stem and branches of eleven tropical hardwoods under Kerala condition and reported that the most common pattern of radial variation was an initial increase in fibre length which reached a maximum and then decreased toward the bark. However, the radial pattern of variation often differed not only between species but also between levels within the tree in certain species. Fibre length followed a nearly linear increase in branches from the pith to the bark indicating juvenile growth.

5.2.3 Tissue proportions

Fibre and parenchyma percentages in species averages showed significant difference between species. Vessel and ray percent were not found to be significant each other. Moreover none of the species studied except ray percent showed within species variation with regard to tissue proportions. Maximum value for species averages in fibre percent was shown by *P. dalbergioides,* followed by *S. macrophylla* and *P. mooniana.* Wood generally contains huge proportion of fibres. Even though *P. mooniana* possess considerable proportion of fibres compared to the parenchyma, because of the lack of standard method to determine the tissue proportion, parenchyma showed highest percent. Since banded and confluent parenchyma was associated with the vessels, counting around the vessel became biased towards the parenchyma proportion. Therefore fibre percent should definitely play an important role for increased specific gravity in *P. mooniana.*

Radial variation within species was non significant with regard to fibre percent. *P. dalbergioides* and *P. mooniana* showed a decreasing trend in fibre percent towards periphery. Ismail et al. (1995) reported a declining trend for fibre proportion in *Neolamarchia cadamba* towards periphery from the pith position. A similar result was observed by Bosman et al. (1994) for *Shorea leprosula* and *S. parvlfolia.* The decreasing trend from pith to bark of fibre proportion was in accordance with the slight increase of ray proportion. Taylor and Wooten (1973) stated that the increase of one cell type must necessarily be accompanied by the decrease of at least one other cell type.

Ray proportion showed an increasing trend from pith towards periphery in the case of *P. mooniana.* Similar pattern of radial change in ray percent change was observed by Ismail et al. (1995) in *Neolamarchia cadamba. P. dalbergioides* showed a decreasing trend towards middle thereafter an increasing trend towards periphery. *S. macrophylla* initially found to have an increasing trend towards middle and latter showed a decreasing trend towards periphery.

5.3 MECHANICAL PROPERTIES

Entire mechanical properties were found to be higher in *P. mooniana*. *S. macrophylla* and *P. dalbergioides* showed homogeneous values in all the properties under compression parallel to grain, compression perpendicular to grain and static bending tests. Highest mechanical properties in *P. mooniana* may be attributed to its high oven dry specific gravity and anatomical features.

Compression parallel to the grain test at both air dry condition and green condition showed that compressive stress at limit of proportionality were higher for *P. mooniana* followed by *P. dalbergioides* and *S. macrophylla*. CS at LP value of teak was lower than that of *P. mooniana*. Latter two species showed lower values compared to teak. Maximum crushing stress also followed the same pattern of variation as that of CS at LP. *P. dalbergioides* showed lower value for maximum crushing stress compared to the values of natural grown *P. dalbergioides* reported by Limaye (1933) and higher value, compared to those reported for 22 year old *P. dalbergioides* plantations in Karnataka by Shukla et al. (1999). Modulus of elasticity was also found to be higher in *P. mooniana* than teak value reported by Sekhar (1988), followed by *P. dalbergioides* and *S. macrophylla*. Higher values for MOE in *P. mooniana* may be attributed to its high oven dry specific gravity and low oven dry moisture content compared to other two species.

Compression perpendicular to the grain test showed that Compressive stress at limit of proportionality was found to be higher for *P. mooniana*, followed by *S. macrophylla* and *P. dalbergioides*. CS at LP value perpendicular to grain for *P. mooniana* was higher than that of teak values reported by Sekhar (1988). *S. macrophylla* showed the third highest value after *P. mooniana* and *T. grandis*. All the other mechanical properties were higher for *P. dalbergioides* after *P. mooniana* and teak. CS at LP value perpendicular to grain in *P. dalbergioides* as well as other species in the study including teak showed lower value with respect to the CS at LP value of natural grown *P. dalbergioides* (172.23) by Limaye (1933). 22 year old *P. dalbergioides* plantations in Karnataka showed higher values (265.94) than the above mentioned species (Shukla et al., 1999).

With regard to static bending test, FS at LP values were higher for *P. mooniana* followed by *P. dalbergioides* and *S. macrophylla*. The value obtained in this species for *P. mooniana* was higher than the value reported for teak by Sekhar (1988). The Latter two species showed lower values as compared to teak. Values of *P. dalbergioides* was lower compared to the FS at LP value reported for natural grown *P. dalbergioides* by Limaye (1933) but was higher than those reported for 22 year old *P. dalbergioides* plantations (439.90) in Karnataka by Shukla et al.(1999). Modulus of rupture and modulus of elasticity values were higher for *P. mooniana* followed by *P. dalbergioides* and *S. macrophylla*. MOR and MOE values were higher for teak compared to *P. mooniana, P. dalbergioides* and *S. macrophylla*. Limaye (1933) reported higher values for natural grown *P. dalbergioides* plantation for MOE and MOR as compared to the present values for *P. dalbergioides*. 22 year old plantations of *P. dalbergioides* from Karnataka showed lower values for MOE (74234.89) and MOR (628.03) compared to corresponding values of *P. dalbergioides* from the present study. Vrolijk et al. (1962) reported that MOE and MOR of *P. mooniana* specimens (50 × 50 mm in section, 700 mm in span) with a 12.3 % moisture content were 163867.40 kg/m^2 and 1542.82 kg/m^2 respectively which were higher than those reported for the *P. mooniana* in the present study. Ishiguru et al. (2011) reported similar values for MOE (157647 kg/m^2) and MOR (1425.55 kg/m^2) in *P. mooniana* as reported by Vrolijk et al. (1962).

Any significant differences in mechanical performance between species are usually attributed to the radial changes in wood density or anatomical structure and not to whether the sample is heartwood or sapwood, per se (Panshin and De Zeeuw, 1980). Among the rare reports, Arganbright (1971), 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.

Table 49. Comparison of wood properties of *P. dalbergioides*, *S. macrophylla* and *P. mooniana* with teak and natural grown *P. dalbergioides*

Sl No	Wood properties	*Pterocarpus dalbergioides*	*Swietenia macrophylla*	*Pericopsis mooniana*	*Tectona grandis* (Sekhar, 1988)	Natural grown *P. dalbergioides* (Limaye, 1933)
1	Specific gravity (oven dry)	0.531	0.526	0.781	0.604	0.644
2	Moisture content oven dry (%)	28.44	30.54	20.89	76.6	8.3
3	Radial shrinkage (%)	2.78	3.58	10.17	2.30	3.3
4	Tangential shrinkage (%) (green to oven dry)	4.14	4.63	12.28	4.80	4.4
5	Static bending					
	a) Fibre stress at limit of proportionality (kg/cm^2)	612.34	535.91	877.68	651.00	659.44
	b)Modulus of rupture (kg/cm^2)	849.81	766.01	1294.85	959.00	1069.37
	c)Modulus of elasticity(Kg/cm^2)	82771.39	72641.44	100778.03	119600	125220.39
6	Compression parallel to grain					
	a) compressive stress at limit of proportionality (kg/cm^2)	343.68	319.94	444.32	376.00	----
	b)Maximum crushing stress(kg/cm^2)	452.71	419.65	574.48	532.00	644.05
	c)Modulus of elasticity (kg/cm^2)	50657.76	36532.81	60289.15	137400	-------
7	Compression perpendicular to grain					
	a)Compressive stress at limit of proportionality (kg/cm^2)	90.17	94.77	160.87	101.00	172.23

5.4 Interrelation ship between wood properties and regression analysis

Correlation analysis revealed that various anatomical properties were correlated negatively and positively with their corresponding mechanical features at species level. In the case of *P. dalbergioides* vessel area was positively correlated with MOR and ML values from the compression parallel to the grain test. Fibre length was positively correlated with HS at ML at dry condition. Fibre wall thickness was found to be positively correlated with HS at LP in the static bending test.

Regression analysis showed that most of the anatomical properties were linearly related to their corresponding mechanical characteristics. Vessel diameter and specific gravity showed a quadratic relationship in the case of *P.dalbergioides*. There was difficulty in developing regression equation, because of the smaller sample size.

In the case of *S. macrophylla,* specific gravity was positively correlated with the work to maximum load and modulus of elasticity in compression parallel to grain. Modulus of rupture in the static bending test also showed a positive correlation with specific gravity. Even though *P. mooniana* showed a near perfect correlation between various mechanical properties and anatomical properties, because of the limited sample availability as replicates, the relationship could not be considered as reliable one for further discussion.

Zhang (1997) examined the specific gravity -mechanical property relationship at species level based on the data set of specimen tests on 16 timber species belonging to four distinct wood categories, and reported that MOR is most closely and almost linearly related to specific gravity, followed by maximum crushing strength (Cmax), whereas MOE is poorly and least linearly related to specific gravity. In general, the relationship between MOE and specific gravity in a species from the ring-porous category is stronger than in a species from the diffuse porous category. In addition, MOE in a softwood species is generally less related to specific gravity as compared to a hardwood species.

The relationship between specific gravity and mechanical properties within a species has been studied for decades. It is widely assumed (Liska, 1965) that wood specific gravity is linearly related to wood mechanical properties, and many studies reported a significant linear relationship between mechanical properties and specific gravity (Kellogg and Ifju, 1962; Liska, 1965; Pearson and Gilmore, 1971; Bendtsen and Ethington, 1972; Schniewind and Gammon, 1983; Shepard and Shottafer, 1992; Zhang, 1992). However, a poor linear relationship between some mechanical properties and specific gravity was also noted (McAlister, 1976; Leclercq, 1980; Schniewind and Gammon, 1983). Liska (1965) reported that a straightline relationship in Douglas fir was justified, but a few studies reported that a curvilinear equation was better than the linear one at predicting wood mechanical properties in loblolly pine (Biblis, 1969a, 1969b; Biblis and Fitzgerald, 1970).

References

REFERENCES

Adamopoulos, S. and Voulgaridis, E. 2002. Within tree variation in growth rate and cell dimensions in the wood of black locust (*Robinia pseudoacacia*) IAWA J., 23 (2): 191–199.

Aggarwal, P.K., Chauhan, S.S., and Karmarkar, A. 2002. Variation in growth strain, volumetric shrinkage and modulus of elasticity and their inter-relationship in *Acacia auriculiformis*. J. Trop. For. Prod., 8 (2): 135–142.

Albrektson, A. 1984. Sapwood basal area and needle mass of Scots pine (*Pinus sylvestris L.*) trees in central Sweden. Forestry, 57: 35– 43.

Alonzo, D.S., Natividad, R.A., Tordilla, W.M. 1998. Utilization of some ITPS in the Philippines: status, prospects and technological breakthroughs. The Philippine Lumberman, 44 (1): 6-14.

Alvin, K.L., Murphy, R.J. 1988. Variation in fibre and parenchyma wall thickness in culms of the bamboo Sinobambusa tootsik. IAWA Bulletin. n.s., 9: 353-361.

Amarasekera, H.S. 1996. Alternative timber species; A review of their properties and uses. In: Amarasekera, H.S. and Banyard, S.G. (Ed.), Forestry for Development. Proceedings of the Annual Forestry Symposium. 1995, December. Sri Lanka. Department of Forestry and Environmental Sciences, pp. 76-88.

Amarasekera, H.S. and Denne, M. 2002. Effects of crown size on wood characteristics of Corsican pine in relation to definitions of juvenile wood, crown formed wood and core wood. Forestry, 75(1): 51-61.

Amidon, T.E. 1981. Effect of the wood properties o f hard woods on kraft paper properties. Tapqi., 64: 123-126.

Amos, G.L., Bisser, I.J. and Dadswell, R.E.1950. Wood structure in relation to growth in *Eucalyptus gigantea* Hook. f. Aust. J. Sci. Res., 83: 393- 412.

Andrews, E.K. 1986. Impact of fibre morphology and chemical composition on the kraft process and subsequent handsheet properties. R and D Conf TAPPI Proc, Raleigh, North Carolina, pp. 111-119.

Anonymous, 1978. Leucaena: the miracle tree. Africa, 86: 75pp.

Fuentes, A.R.L., and Hernandez, R. 2008. Effect of extractives and anatomical structure on the mechanical properties of the wood of caoba (*Swietenia macrophylla*) King. Colom. Forestry J., 11 (21): 137-147.

Arganbright, D.G. 1971. Influence of extractives on bending strength of Redwood (*Sequoia sempervirens*). Wood Fiber Sci., 2: 367–372.

Ashton, P.M.S., Gunatilleke, C.V.S., de Zoysa, N.D., Wjiesuriya, I.A.U.N. and Dassanayake, M.D. 1997. A field guide to the common trees and shrubs of Sri Lanka, Wildlife Heritage Trust Press, Colombo, Sri Lanka.

Baas, P. 1982. New perspectives in wood anatomy. W. Jung Publishers, The Hague, Netherlands, 252 p.

Baas, P., Werker, E. and Fahn, A. 1983. Some ecological trends in vessel characters. IAWA J., 4: 141-159.

Baas, P. and Schweingruber, F.H. 1987. Ecological trend in the wood anatomy of trees, shrubs and climbers. IAWA J., 8: 245-274.

Bamber, R.K. and Curtin, R.A. 1974. Some properties o f wood in black butt trees of two ages . Aus. Forestry., 36: 226-234.

Bamber, R.K., Home, R. and Higgs, G.A. 1982. Effect of fast growth on the wood properties of *Eucalyptus grandis*. Austr. For. Res., 12: 163 -167.

Bamber, R.K. and Burley, J. 1983. The wood properties of *Pinus radiata*. Common W. Agr. Bur, England, 84p.

Bamber, R.K. and Fukazawa, K. 1985. Sapwood and heartwood: A review. Forest Products Abstr., 8: 265-278.

Bancalari, E.M.A., Perry, D.A and Marshall, J.D. 1987. Leaf area sapwood relationships in adjacent young Douglas-fir stands with different early growth rates. Can. J. For. Res., 17: 174 –180.

Bao, F.C. and Jiang, Z.H. 1994. Studies on the properties of wood from fast-growing forest plantation. World Forestry Research Vol. 7. Ministry of Forestry, Beijing, 340p.

Barber, N.N. and Meylan, B.A. 1964. The anisotropic shrinkage of wood: a theoretical model. Holzforschung, 18: 146–156.

Barnes, R.D., Woodend, J.J., Schweppenhauser, M.A. and Mullen, L.J. 1977. Variation in diameter growth and wood density in six year old provenance trials of *Pinus caribaea* on five sites in Rhodesia. Silvae Genet., 26 (5-6): 163-167.

Barnett, J.R. and Jeronimidis, G. 2003. Wood quality and its biological basis. Blackwell, Oxford, 304p.

Bauch, J., Schweers, W. and Berndt, H. 1974. Lignification during heartwood formation: Comparative study of rays and bordered pit membranes in coniferous woods. Holzforschung, 28: 86-91.

Becker, P., Meinzer, F.C. and Wullschleger, S.D. 2000. Hydraulic limitation of tree height: a critique. Funct. Ecol., 14: 4-11.

Bendtsen, B.A. and Ethington, R.L. 1972: Properties of major southern pines. Part II. Structural properties and specific gravity. USDA Forest Service, Res. Pap. Forest Prod. Lab. 177, Madison, WI.

Bendtsen, B.A. 1978. Properties of wood from improved and intensively managed trees. Forest Prod. J., 28: 61- 72.

Bergstrom, B. 2003. Chemical and structural changes during heartwood formation in Pinus sylvestris. Forestry, 76: 45-53.

Berninger, F. and Nikinmaa, E. 1997. Implications of varying pipe model relationships on Scots pine growth in different climates. Funct. Ecol., 11: 146–156.

Bhat, K.M. 1985. Properties of selected lesser known tropical hardwoods. J. Ind. Acad. Wood Sci., 16(1): 26-35.

Bhat, K.M. 1995. A note on heartwood proportion and wood density of 8 year-old teak. Indian For., 121(6): 515–517.

Bhat, K.M., Bhat, K.V. and Dhamodaran, T.K. 1989. Fibre length variation in stem and branches of eleven tropical hardwoods. IAWA Bull. n.s., 10: 63-70.

Bhat, K.M., Priya, P.B. and Rugmini, P. 2001. Characterization of juvenile wood in teak. Wood Sci. Technol., 34: 517–532.

Biblis, E.J. 1969a. Tensile properties of loblolly pine growth zones. Wood and Fiber Sci., 1:18-28

Biblis, E.J. 1969b. Transitional variation and relationships among properties within loblolly pine growth rings. Wood Sci. Technol., 3:14-24.

Biblis, E.J. and Fitzgerald, J. D. 1970. Shear properties of loblolly pine growth zones. Wood Sci., 2:193-202

Bird, P.R. 2000. Farm Forestry in Southern Australia: A Focus on Clearwood Production of Speciality Timbers. State of Victoria, Department of Natural Resources and Environment, Victoria, 264 p.

Bisset, I.J.W. and Dadswell, H.E. 1950. The variation of cell length with in one growth ring of certain angiosperms and gymnosperms. Aust. Forestry., 14: 17 -29.

Blundell, A.G. and Rodan, B.D. 2003. Mahogany and CITES: moving beyond the veneer of legality. Oryx, 37(1): 85-90.

Blundell, A.G. and Gullison, R.E. 2003. Poor regulatory capacity limits the ability of science to influence the management of mahogany. Forest Policy Econ., 5: 395-405.

Bootle, K.R. 1983. Wood in Australia. Mc Graw-Hill Book Company Australia Pty Ltd, Sydney, 443 p.

Boland, D.J., Brooker, M.I.H., Chippendale, G.M., Hall, N., Hyland, B.P.M., Johnston, R.D., Kleinig, D.A. and Turner, J.D. 1984. Forest Trees of Australia. CSIRO. 4th edn Nelson and CSIRO, Melbourne, Australia, 687 p.

Borralho, N.M.G., Cotterill, P.P. and Kanowski, P.J. 1992. Genetic parameters and gains expected from selection for dry weight in Eucalyptus globulus ssp. globulus in Portugal. For. Sci., 38: 80–94.

Bosman, M.T.M. 1997. Variability in wood properties of six year old planted meranti trees (*Shorea leprosula, Shorea parvifolia* and *Shorea pauciflora,* Dipterocarpaceae). IAWA J., 18(4): 405–413.

Bosman, M.T.M., de Kort, I.M.K., van Genderen and Baas, P. 1994. Radial variation in wood properties of naturally and plantation grown light red rnerandi (Shorea, Dipterocarpaeceae).IAWA J., 15 : 111 -120.

Bosshard, H.H. 1983. Holzkunde. Vol. 2. Birkhaeuser Verlag, Basel.

Boyd, J.D. 1974. Anisotropic shrinkage of wood: Identification of the dominant determinants. Mokuzai Gakkaishi, 20: 473–482.

Bissing, D.R. 1982. Variation in qualitative anatomical features of the xylem of selected dicotyledonous woods in relation to water availability. Bull Torrey Bot. Club, 109: 371-384.

Brewbaker, J.L. and Hutton, E.M. 1979. Leucaena -Versatile tree legume. In G.A. Ritchie (ed.), New agricultural crops, AAAS Selected Symposium. Boulder, Colorado: Westview Press.

Briscoe, C.B., Harris, J.B., and Wyckoff, F. 1963. Variation of specific gravity in plantation-grown trees of big-leaf mahogany. Caribb. Forestry, 24: 67- 74.

Brix, H. and Mitchell, A.K. 1983. Thinning and nitrogen fertilization effects on sapwood development and relationships of foliage quantity to sapwood area and basal area in Douglas-fir. Can. J. For. Res., 13: 384–389.

Brooks, J.R., and Jiang, L. 2009. Comparison of prediction equations for estimating inside bark diameters for yellow-poplar, red maple, and red pine in West Virginia. North J. Appl. For., 26:5–8.

Burley, J. and Wood, P.J. 1976. A manual on species and provenance research with particular reference to the tropics. CFI Trop For Pap10, 226p.

Butterfield, R.P., Crook, R.P., Adams, R., and Morris, R. 1993. Radial variation in wood specific gravity, fibre length and vessel area for two Central American hardwoods: *Hyeronima alchomeoides* and *Vochysia guatemalensis*. IAWA J., 14: 153-161.

Callaham, R.Z. 1964. Provenance research: investigation of genetic diversity associated with geography. Unasylva, 18:40-50.

Callaway, R.M., DeLucia, E.H. and Schlesinger, W.H.1994. Biomass allocation of montane and desert ponderosa pine: an analog for response to climate change. Ecology, 75: 1474 –1481.

Cao, Q.V. and Pepper, W.D. 1986. Predicting inside bark diameter for shortleaf, loblolly and longleaf pines. South. J. Appl. For., 10(1-4): 220-224.

Carlquist, S. 1966. Wood anatomy of Compositae: a summary, with comments on factors controlling wood evolution. Aliso., 6: 25-44.

Carlquist, S. 1975. Ecological strategies of xylem evolution. Univ. of California Press, Berkeley.

Castro, D.F., Williamson, G.B. and Jesus, R.M.D. 1993. Radial variation in the wood specific gravity of *Joannesia princeps*: the roles of age and diameter. Biotropica, 25:176-182.

Cermak, J., Cienciala, E., Kucera, J. and Hallgren, J.E. 1992. Radial velocity profiles of water flow in trunks of Norway spruce and oak and the response of spruce to severing. Tree Physiol., 10: 367–380.

Chafe, S.C. 1990. Relationship among growth strain, density and strength properties in two species of Eucalyptus. Holzforschung, 44(6): 431–437.

Chafe, S.C. 1994. Specific gravity and bending stress in trees of *Eucalyptus regnans*. Holzforschung, 48: 233 – 235.

Chalk, L. 1951.Water and growth of Douglas-fir. Q. J. For., 45: 237-242.

Chudnoff, M. 1961. The physical and mechanical properties of Eucalyptus camaldulensis. Isr. J. Agr. Res., 39p.

Chudoff, M. 1976. Density of tropical timbers as influenced by climatic life zones. Common wealth Forestry Review, 55: 203–217.

Chudnoff, M. and Geary, T.F. 1973. On the heritability of wood density in *Swietenia macrophylla*. Turriablba, 23: 359-360.

Climent, J., Chambel, M.R., Perez, E., Gil, L. and Pardos, J. 2002. Relationship between heartwood radius and early radial growth, tree age, and climate in *Pinus canariensis*. Can. J. For. Res., 32:3–111.

Comstock, G.L. 1965. Longitudinal permeability of green eastern hemlock. Forest Prod. J., 15: 441– 449.

Constantino, L.F. and Haley, D.1988.Trends in wood quality for the British Columbia Coast and the United States, Pacific Northwest side, Westside. Forest Sci., 34: 176-189.

Corcuera, L., Camarero, J.J. and Pelegrin, G.E. 2004. Effect of a severe drought on *Quercus ilex* radial growth and xylem anatomy. Trees struct. Funct., 18: 83-92.

Cruiziat, P., Cochard, H. and Ameglio, T. 2002. Hydraulic architecture of trees: main concepts and results. Ann. Forest Sci., 59: 723-752.

Dadswell, H.E. 1958. Wood structure variations occurring during tree growth and their influence on properties. J. Inst. Wood Sci., 1: 11–32.

Dadswell, H.E. 1972. The anatomy of eucalypt woods. CSIRO Division of Applied Chemistry Technological Paper No. 66.

Dean, T.J. and Long, J.N. 1986. Variation in sapwood area-leaf area relations within two stands of lodge pole pine. For. Sci., 32: 749–758.

Donaldson, L.A., Grace, J. and Downes, G.M. 2004. Within tree variation in anatomical properties of compression wood in radiata pine. IAWA J., 25 (3): 253–271.

Downes, G.M. and Raymond, C.A. 1997. Variation in wood density in plantation eucalypts. In: (Downes G.M. et al. (eds) Sampling Plantation Eucalypts for Wood and Fibre Properties. Appendix 1, pp. 88-99. CSIRO Publishing, Australia. 132 p.

Downes, G.M., Hudson, I.L., Raymond, C.A., Dean, A.J., Michell, L.R., Schimleck, Evans, R. and Muneri, A. 1997. Sampling Eucalypts for wood and fibre properties. CSIRO Publishing, Australia, 132p.

Ellmore, G.S. and Ewers, F.W. 1986. Fluid flow in the outermost xylem increment of a ring-porous tree, *Ulmus americana*. Amer. J. Bot., 73: 1771–1774.

Enquist, B.J., West, G.B., Charnov, E.L. and Brown, J.H. 1999. Allometric scaling of production and life-history variation in vascular plants. Nature, 401: 907 -911.

Espinoza J.A. 2004. Within-tree density gradient in Gmelina arborea in Venezuela. New For., 28: 309-317.

February, E.C. 1993. Sensitivity of xylem vessel size and frequency to rainfall and temperature: implications for paleontology. Palaeontologia Africana, 30: 91-95.

February, E.C., Stock, W.D., Bond, W.J. and Roux, L.D.J. 1995. Relationships between water availability and selected vessel characteristics in *Eucalyptus grandis* and two hybrids. IAWA J., 16 (3): 269 -276.

Ferreira, M. 1968. Status of the variation of basic density of the wood of Eucalyptus alba and Eucalyptus saligna, Univ Sao Paulo Piracicaba Brasil, 71 p.

Ferreira, M.1972. Variation of wood basic density in commercial plantations of Eucalyptus grandis at ages of 11, 12, 13, 14 and 16 years. IPEF, 4: 65-75.

Findlay, W.P.K. 1962. The preservation of timber. Adam and Charles Black, London, 162p.

Flaete, P.O. and Vadla, K. 2008. Predicting vertical heartwood diameter profiles of Scots pine (*Pinus sylvestris* L.) based on data from the forest. *In:* Proceedings of the 51st International Convention of Society of Wood Science and Technology, November 10-12, Chile, 8 pp.

Frey-Wyssling, A. and Bosshard, H.H. 1959. Cytology of the ray cells in sapwood and heartwood. Holzforschung, 13: 129-137.

Fuentes, L.R.A. and Hernandez, R. 2008. Effect of extractives, anatomy and structure in the mechanical properties of wood mahogany, Swietenia macrophylla King. Colomb. Forestry J., 11: 137-147.

Fujiwara, S. 1992. Anatomy and properties of Japanese hardwoods II. Variation of dimensions of ray cells and their relation to basic density. IAWA Bull. n. s., 13: 397–402.

Fukazawa, K.1983. Juvenile wood of hardwoods. Div 5 IUFRO Conf. Madison, Wisconsinsin, pp. 28-29.

Furukawa, I., Nakayama, T. Sakuno, T. and Kishimoto, J. 1983. Wood quality of small hardwoods, horizontal variations in the length of fibers and vessel elements in trees with storeyed and non storeyed wood (*Robinia pseudoacacia, Diospyros kaki, Tilia japonica, Alnus hirsuta*). Bull. Fac. Agric. Tottori Univ., 35: 42– 49.

Fukazawa, K. 1984. Juvenile wood of hardwoods judged by density variation. IAWA Bull. n.s., 5: 65–73.

Furukawa, I. and Hashizume, H. 1987. The influence of fertilization and improvement cutting on the wood quality of mature kunugi trees. *Mokuzai Gakkaishi*, 33: 443– 449.

Gartner, B.L. 1991. Stem hydraulic properties of vines vs. shrubs of western poison oak, Toxicodendron diversilobum. Oecologia, 87: 180–189.

Gartner, B.L. 2002. Sapwood and inner bark quantities relation to leaf area and wood density in Douglas-fir. IAWA J., 23(3): 267-285.

Gartner, B.L., Lei, H. and Milota, M.R. 1997. Variation in the anatomy and specific gravity of wood within and between trees of red alder (Alnus rubra Bong.). Wood Fiber Sci., 29: 10–20.

Gartner, B.L., Moore, J.R. and Gardiner, B.A. 2001. Why is there so much air in sapwood? In: M. Kaennel Dobbertin and O.U. Braker (eds.), Tree rings and people: International conference on the future of dendrochronology. Swiss Federal Research Institute WSI, Birmensdorf, Switzerland, pp. 200-201.

Ghouse, A.K.M. and Siddiqui, F.A. 1976. Cell length variation in phloem fibres within the bark of four tropical fruit trees *Aegle marmelos, Mangifera indica, Syzygium cumini*, and *Zizyphus mauritiana*. Blumea, 23: 13–16.

Gominho, J. and Pereira, H. 2000. Variability of heartwood content in plantation grown *Eucalyptus globulus* Labill. Wood Fiber Sci., 32(2):189–192.

Gominho, J. and Pereira, H. 2005. The influence of tree spacing in heartwood content in *Eucalyptus globulus* Labill. Wood Fiber Sci., 37(4):582–590.

Gominho, J., Figueira, J., Rodrigues, J. and Pereira, H. 2001. Within-tree variation of heartwood, extractives and wood density in the eucalypt hybrid urograndis (*Eucalyptus grandis*) (*E. urophyla*). Wood Fiber Sci., 33(1):3–8.

Gonzalez, E. and Fisher, R. 1998. Variation in selected wood properties of Vochysia guatemalensis from four sites in Costa Rica. For. Sci., 44: 185–191.

Gordon, A. 1983. Estimating bark thickness of *Pinus radiata*. New Zeal-and J. Forestry Sci., 13(3): 340-348.

Grabner, M. 2002. Relationships among wood quality indicators of Larch wood grown in Europe. Diploma thesis, Universitat fur Bodenkultur Vienna, Austria.

Greaves, B.L., Borralho, N.M.G., Raymond C.A. and Farrington, A. 1996. Use of Pilodyn for the indirect selection of basic density in Eucalyptus nitens. Can. J. For. Res., 26: 1643-1650.

Grier, C.C. and Waring, R.H. 1974. Conifer foliage mass related to sapwood area. For. Sci., 20: 205-206.

Grogan, J., Barreto, P. and Verissimo, A. 2002. Mahogany in the Brazilian Amazon: ecology and perspectives on management. Belem, Brazil, Amazon, 58p.

Guiher, J.K. 1965. Effect of rings-per-inch on specific gravity of red oak. For Prod. J., 15: 409– 411.

Gupta, D.P.R.1969.Wood water relationship in Pterocarpus dalbergioides, Indian For., 95(3):165-72.

Guyette, R.P. and Stambaugh, M. 2003. The age and density of ancient and modern oak wood in streams and sediments. IAWA J., 24: 345–353.

Hai, P.H., Hannrup, B., Harwood, C., Jansson, G. and Ban, D.V. 2010. Wood stiffness and strength as selection traits for sawn timber in Acacia auriculiformis. Can. J. For. Res., 40: 322–329.

Hans, A.S., Burley, J. and Williamson, P. 1972. Wood quality in *Eucalyptus grandis* grown in Zambia. Holzforsch, 26: 138-141.

Harris, J.M. 1961. A survey of the wood properties of radiate pine grown in the Kaingaroa Forest. For Prod Rep 76 For Res Inst N Z For Serv, 1-16.

Haslett, A.N. and Young, G.D. 1990. Plantation grown tropical timbers. Wood property and processing evaluation procedures to improve usage. J. Trop. Forest Sci., 3(2):131-139.

Haygreen, G.J. and Bowyer, J.L. 1996. Specific gravity. Chapter 9. Forest Products and Wood Science: An Introduction. 3rd edn. Iowa State Press, Ames, Iowa, USA.

Hazenberg, G. and Yang, K.C. The relationship of tree age with sapwood and heart wood width in black spruce, *Picea mariana* (Mill.) B.S.P. (In preparation).

Heath, L.S., Hansen, M., Smith, J.E., Miles, P.D., and Smith, B.W. 2009. Investigation into calculating tree biomass and carbon in the FIADB using a biomass expansion factor approach. In: McWil-liams W, Moisen G, Czaplewski R (eds) Forest inventory and analysis (FIA) symposium 2008; October 21–23, 2008. Park City, UT. Proceedings RMRS-P-56CD. US Forest Service Rocky Mountain Research Station. Fort Collins, CO, 24 pp.

Hejnowicz, A. and Hejnowicz, Z. 1959. Variations of length of vessel members and fibers in the trunk of *Robinia pseudoacacia*. Acta. Soc. Bot. Pol., 28: 453– 460.

Herpka, I. 1965.On the variability of the wood fibres and the specific gravity in a natural population of white willow (Salix alba) in the inundation area of the Danube. Inter Poplar Comm Novi Sad, Yugoslavia 12th session, 1-9.

Higgins, H.G. 1984. Pulp and paper. In: Hillis WE, Brown AG (eds) Eucalyptus for wood production. CSIRO, Melbourne, p 290.

Hillis, W.E. and Ditchburne, N. 1974. The prediction of heart wood diameter in radiata pine trees. Can. J. For. Res., 4: 524-529.

Hillis, W.E. 1978. Wood quality and utilization. In: Hillis, W.E. and Brown, A.G. (eds) Eucalypts for Wood Production. CSIRO, Melbourne, Australia, pp. 259–289.

Isebrands, J.G. 1972. The proportion of wood elements within eastern cotton wood. Wood Sci., 5: 139-146.

Isebrands, J.G. and Hunt, C.M. 1975. Growth and wood properties of rapid grown Japanese larch. Wood Fiber sci., 7: 119-128.

Ishiguri, F., Hiraiwa, T., Iizuka, K., Yokota, S., Priadi, D., Sumiasri, N., Yoshizawa, N. 2009. Radial variation of anatomical characteristics in *Paraserianthes falcataria* planted in Indonesia, IAWA J., 30 (3): 343–352.

Ishiguri, F., Wahyudi, I., Takeuchi, M., Takashima, Y., Iizuka, K., Yokota, S., and Yoshizawa, N. 2011. Wood properties of Pericopsis mooniana grown in a plantation in Indonesia. Wood Sci., 57:241–246.

ISI (Indian Standards Institution). 1986. Indian standard method of testing small clear specimens of timber. IS: 1708, Bureau of Indian Standards (BIS), New Delhi, 42p.

ISI (Indian Standards Institution). 1990. Indian standard method of sampling of modal trees and logs for timber testing and their conversion. IS: 2455, Bureau of Indian Standards (BIS), New Delhi, 6p.

Ismail, J., Jusoh, M.Z., and Sahri, M.H. 1995. Anatomical variation in planted kelempayan (*Neolamarckia cadamba*, rubiaceae). IAWA Journal, 16 (3): 277 – 287.

Jain, J.C. 1969. A note on Eucalyptus hybrid as timber. Ind. For., 95: 29-32.

Jara, A.A., Bello, E.D., Castillo, S.V.A., Fernandez, V.A., and Madamba, P.S. 2008. Use of relative density-based schedules in kiln-drying big-leafed

Hillis, W.E. 1987. Heartwood and tree exudates. Springer-Verlag, Berlin-Heidelberg- New York- Tokyo, 268pp.

Huang, C.L., Lindstro, M.H., Nakada, R. and Ralston, J. 2003. Cell wall structure and wood properties determined by acoustics- a selective review. Holz Roh Werkst, 61(5): 321–335.

Hudson, I., Wilson, L., Sandercock, C. and Sands, R. 1995. Within-ring variability of wood micro structure in Eucalyptus nitens. In: Proc. CRCTHF-IUFRO Conference. Eucalypt Plantations: Improving Fibre Yield and Quality. Hobart, Tasmania, p.110-115.

Hudson, I., Wilson, L. and Beveren, K.V. 1998. Vessel and fibre property variation in *Eucalyptus globulus* and *Eucalyptus nitens*: some preliminary results. IAWA J., 19: 111-130.

Hunter, A.G. and Goggans, J.R.1968. Variation in specific gravity, diameter growth, and coloured heartwood of sweetgum in Alabama. Tappi., 51: 76-79.

Husch, B., Beers, T.W. and Kershaw, J.A. 2003. Forest mensuration, 4th edn. Wiley, New York, 133p.

Ilic, J., Boland, D., McDonald, M., Downes, G. and Blakemore, P. 2000. Wood Density Phase one State of Knowledge, National Carbon Accounting System. Australian Greenhouse Office, Commonwealth of Australia. Technical Report No. 18, 218 p.

Innes, T. 2007. Processing and wood properties of four ages of *Eucalyptus oblique*. Holz Roh Werkst, 65(3): 197–200.

Isebrands, J.G. 1972. The proportion of wood elements within eastern cotton wood. Wood Sci., 5: 139-146.

Isebrands, J.G. and Hunt, C.M. 1975. Growth and wood properties of rapid grown Japanese larch. Wood Fiber sci., 7: 119-128.

Ishiguri, F., Hiraiwa, T., Iizuka, K., Yokota, S., Priadi, D., Sumiasri, N., Yoshizawa, N. 2009. Radial variation of anatomical characteristics in *Paraserianthes falcataria* planted in Indonesia, IAWA J., 30 (3): 343–352.

Ishiguri, F., Wahyudi, I., Takeuchi, M., Takashima, Y., Iizuka, K., Yokota, S., and Yoshizawa, N. 2011. Wood properties of Pericopsis mooniana grown in a plantation in Indonesia. Wood Sci., 57:241–246.

ISI (Indian Standards Institution). 1986. Indian standard method of testing small clear specimens of timber. IS: 1708, Bureau of Indian Standards (BIS), New Delhi, 42p.

ISI (Indian Standards Institution). 1990. Indian standard method of sampling of modal trees and logs for timber testing and their conversion. IS: 2455, Bureau of Indian Standards (BIS), New Delhi, 6p.

Ismail, J., Jusoh, M.Z., and Sahri, M.H. 1995. Anatomical variation in planted kelempayan (*Neolamarckia cadamba*, rubiaceae). IAWA Journal, 16 (3): 277 – 287.

Jain, J.C. 1969. A note on Eucalyptus hybrid as timber. Ind. For., 95: 29-32.

Jara, A.A., Bello, E.D., Castillo, S.V.A., Fernandez, V.A., and Madamba, P.S. 2008. Use of relative density-based schedules in kiln-drying big-leafed mahogany (*Swietenia macrophylla* King) lumber. Philippine J. Sci., 137 (2): 159-167.

Johansen, D. 1940. Plant Microtechnique. McGraw-Hill Book Company, New York.

Johnson, T.S. and Wood, G.B. 1987. Simple linear model reliably predicts bark thickness of radiata pine in the Australian Capital Territory. For. Ecol. Manage., 22: 173–183.

Jorge, F., Quilho, T., and Pereira, H. 2000. Variability of fibre length in wood and bark in Eucalyptus globules. IAWA J., 21 (1): 41–48.

Jayawardana, D.N. and Amarasekara, H.S. 2008. Investigation of the effect of growth rate on the quality of Teak (*Tectona grandis*) wood, Proceedings of the International Forestry and Environment Symposium, 2008; Kalutara, Sri Lanka.

Kammesheidt, L., Lezama, T.A., Franco, W. and Ponczak, M. 2001. History of logging and silvicultural treatments in the western Venezuelan plain forests and the prospects for sustainable forest management. For. Ecol. Manage., 148: 1-20.

Karkkainen, M. 1972. On the proportion of heartwood in Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*). Silva Fenn., 6(3):193–208

Kaufmann, M.R. and Troendle, C.A. 1981. The relationship of leaf area and foliage biomass to sapwood conducting area in four subalpine forest tree species. For. Sci., 27: 477-482.

Keane, M.G. and Weetman, G.F. 1986. Leaf area sap wood cross-sectional area relationships in repressed stands of lodge pole pine. Can. J. For. Res., 17: 205-209.

Keane, M.G. and Weetman, G. F. 1987. Leaf area sapwood cross sectional area relationships in repressed stands of lodge pole pine. Can. J. For. Res., 17: 205-209.

Kellogg, R.M., and Ifju, G. 1962: Influence of specific gravity and certain other factors on the tensile properties of wood. Forest Prod. J., 12:463-470.

Kershaw, J.A. and Maguire, D.A. 2000. Influence of vertical foliage structure on the distribution of stem cross sectional area increment in western hemlock and balsam fir. For. Sci., 46: 86– 94.

Khanduri, A.K., Panwar, P.S. and Jain, J.D. 2000. An assessment of physical and mechanical properties of plantation grown *Grevillea robusta* and *Terminalia myriocarpa.* J. TDA, 46 (3-4): 19-22.

Kim, N., Ochiishi, M., Matsumura, J. and Oda, K. 2008. Variation in wood properties of six natural acacia hybrid clones in northern Vietnam. J. Wood Sci., 54(6): 436-442.

King, D.A. 1981. Tree dimensions: maximizing the rate of height growth in dense stands. Oecologia, 51: 351– 356.

King, D.A., Davis, S.J., Tan, S. and Noor, N.M. 2006. The role of wood density and stem support costs in the growth and mortality of tropical trees. J. Ecol., 94: 670– 680.

Kliger, I.R., Perstorper, M., and Johansson, G. 1998. Bending properties of Norway spruce timber. Comparison between fast- and slow-grown stands and influence of radial position of sawn timber. Ann. For. Sci., 55(3): 349–358.

Knapic, S. and Pereira, H. 2005. Within-tree variation of heartwood and ring width in maritime pine (Pinus pinaster Ait.). For. Ecol. Manage., 210:81-89.

Kolin, B. 1988. Effect of moisture and temperature upon the compression strength parallel to the grain in the wood. Drvna Ind., 39(7-8): 165-175.

Koning-Vrolijk, G.M.C., Jutte S.M., and Hof, T. 1962. Properties of New Guinea woods 1. Nova Guinea , 10:137–175

Kothiyal, V., Shukla, S.R., Sudheendra, R., Kamala, B.S. and Rao, R.V. 1998. Assessment of wood quality of Eucalyptus hybrid from Karnataka, India. J. Trop. For. Prod., 4: 166–173.

Kumar, S. 1998. Dimensional stabilization of wood. Factors influencing shrinkage-swelling behaviour. J. Timb. Dev. Assoc., 64(4): 31-38.

Kuo, M.L. and Arganbright, D.G. 1980. Cellular distribution of extractives in redwood and incense cedar. Part I. Radial variation in cell-wall extractive content. Holzforschung., 34: 17–22.

Laar, A. 2007. Bark thickness and bark volume of *Pinus patula* in South Africa. South Hemisph. For. J., 69:165–168 .

Laasasenaho, J., Melkas, T. and Aldn, S. 2005. Modeling bark thickness of Picea abies with taper curves. For. Ecol. Manage., 206:35–47.

Ladrach, W.E. 1986. Control of wood properties in plantations, IUFRO Congr Ljubljana, Yugoslavia, 369-38pp.

Ladrach, W.E. 2000. Genetic aspects of forestry and their relation to wood. Tropical forestry research: challenges in the new millennium. Proceedings of the International Symposium, Peechi, India: Kerala Forest Research Institute (KFRI), 11-19pp.

Lamb, F.B. 1966. Mahogany of tropical America: its ecology and management. Ann Arbor, Michigan, USA, University of Michigan Press, 220p.

Lamb, A.F.A. 1973. *Pinus caribaea* Vol I. Fast growing timber trees of the lowland tropics, Oxford University press, oxford.

Land, S.B., Dicke, S.G., Tuskan, G.A. and Patterson, P.E. 1983. Genetic, site and within tree variation in specific gravity and moisture content in young sycamore trees. Tappi., 66: 149-155.

Landau, M.H.C. 2004. Interspecific and intersite variation in wood specific gravity of tropical trees. Biotropica, 36: 20 – 32.

Langbour, P., Gerard, J., Guibal, D., and Cros, R.T. 2008. Technical properties of Swietenia macrophylla King planted in Martinique. 298: 3-12.

Langstrom, B. and Hellqvist, C. 1991. Effects of different pruning regimes on growth and sapwood area of Scots pine. For. Ecol. Manage., 44: 239–254.

Larson, P.R. 1960. A physiological consideration of the springwood summerwood transition in red pine. For. Sci., 6: 110-112.

Larson, P.R. 1962. A biological approach to wood quality. TAPPI., 45: 443-448.

Larson, P.R. 1964. Some indirect effects of environment on wood formation. In: The formation of wood in forest trees (cd.M.H.Zimmermann):Acad. Press, New York, pp. 345-365.

Larson, P.R. 1967. Effect of temperature on the growth and wood formation of ten Pinus resinosa sources, Silvae. Genet., 16: 58-65.

Larson, P.R. 1969.Wood formation and the concept of wood quality. Yale Univ Sch For Bull 74, 54pp.

Lassen, L.E. and Okkonen, E.A. 1969. Sapwood thickness of Douglas fir and five other western softwoods. USDA Forest Service Research Paper, FPL 124, Madison, WI.

Laurila, R. 1995. Wood properties and utilization potential of eight fast- growing tropical plantation tree species, J.Trop. For. Prod., 1(2): 209-221.

Leclercq, A. 1980: Relationships between beechwood anatomy and its physico-mechanical properties. IAWA Bull. n.s., 1(1-2):65-71.

Lee, S.S., Teng, S.Y., Lim, M.T. and Razali, A.K. 1999. Discoloration and heart rot of *Acacia mangium* Willd. some preliminary results. J. Trop. For. Sci., 1: 179–177.

Lei, H., Milota, M.R. and Gartner, B.L. 1996: Between- and within-tree variation in the anatomy and specific gravity of wood in Oregon white oak (Quercus garryana Dougl.). IAWA J., 17: 445– 461.

Limaye, V.D. 1933. Properties of wood grown in India. Indian Forest Records. 18(10): 1-70.

Lin, C., Chung, C., Cho, C., and Yang, T. 2012. Tree ring characteristics of 30-year old Swietenia macrophylla plantation trees. Wood Fiber Sci., 44 (2): 1-12.

Liska, J.A. 1965: Research progress on the relationships between density and strength. Proc. the symposium on Density: A key to wood quality, USDA Forest Service, Forest Prod. Lab., Madison, WI, pp. 89-97.

Long, J.N. and Smith, F.W. 1987. Leaf area sap wood area relations of lodge pole pine as influenced by stand density and site index. Can. J. For. Res., 18: 247-250.

Maguire, D.A. and Hann, D.W. 1990. Bark thickness and bark volume in southwestern Douglas-fir. West. J. Appl. For., 5:5–8.

Malan, F.S. 1988. Genetic variation in some growth and wood properties among 18 full sib families of South African grown Eucalyptus grandis: A preliminary investigation. S. A. For. J., 146: 38- 43.

Marchand, P.I. 1984. Sapwood area as an estimation of foliage biomass and projected leaf area for *Abies balsamea* and *Picea rubens*. Can. J. For. Res., 14: 85-87.

Margolis, H.A., Gagnon, R. R., Pothier, D. and Pineau, M. 1988. The adjustment of growth, sapwood area, heartwood area, and sapwood saturated permeability of balsam fir after different intensities of pruning. Can. J. For. Res., 18: 723– 727.

Margolis, H., Oren, R., Whitehead, D. and Kaufmann, M.R. 1995. Leaf area dynamics of conifer forests. In: W.K. Smith and T.M. Hinckley (eds.), Ecophysiology of coniferous forests Academic Press, San Diego, California, pp 181– 223.

Marshall, H.D., Murphy, G.E. and Lachenbruch, B. 2006. Effects of bark thickness estimates on optimal log merchandising. For. Prod. J., 56: 87–92.

Maruzzo, M. M., America, W. M. and Escobin, R. P. 2003. Wood anatomical properties of big-leafed mahogany (*Swietenia macrophylla* King) and malapapaya [*Polycias nodosa* (Blume) Seem.]. FPRDI Journal Laguna: Forest Products Research and Development Institute (FPRDI), 29 (1/2): 132-144.

Mauseth, J.D., Stevenson, J.F. (2004): Theoretical considerations of vessel diameter and conductive safety in populations of vessels. Int. J. Plant Sci., 165(3): 359-368.

Mayhew, J.E. and Newton, A.C. 1998. The silviculture of mahogany. Wallingford, UK, CABI Publishing, 226pp.

McAlister, R.H. 1976: Modulus of elasticity distribution of loblolly pine veneer as related to location within the stern and specific gravity. Forest Prod. J., 26(10):37-39.

McIntosh, D.C. 1957. Transverse shrinkage of red oak and beech. For. Prod. J., 7: 114–120.

McKimm, R.J. and Ilic, J. 1987. Characteristics of the wood of young fast-grown trees of Eucalyptus nitens Maiden with special reference to provenance variation. III. Anatomical and physical characteristics. Aust. For. Res., 17: 19-28.

McKimmy, M.D. 1959. Factors related to variation in specific gravity in young growth Douglas fir. Oregon For Prod Res Cent Bull8, 52pp.

Mencuccini, M. and Grace, J. 1995. Climate influences the leaf area/sapwood area ratio in Scots pine. Tree Physiol., 15: 1–10.

Miranda, I., Gominho, J., Lourenco, A., and Pereira, H. 2006. The influence of irrigation and fertilization on heartwood and sapwood contents in 18-year-old *Eucalyptus globulus* trees. Can. J. For. Res., 36:2675–2683.

Miranda, I., Gominho, J., Lourenco, A., and Pereira, H. 2007. Heartwood, extractives and pulp yield of three Eucalyptus globulus clones grown in two sites. Appita J., 60(6):485–489.

Miranda, I., Gominho, J. and Pereira, H. 2009. Variation of heartwood and sapwood in 18-year-old *Eucalyptus globulus* trees grown with different spacings. Trees, 23: 367–372.

Sahri, M.H., Ashaari, Z., Kader, R.A. and Abdul Latif Mohmod. 1999. Physical and mechanical properties of *Acacia mangium* and *Acacia auriculiformis from different provenances. J. Trop. Agric. Sci.*, 21(2): 73-81.

Monserud, R.A. 1979. Relations between inside and outside bark diameter at breast height for Douglas-fir in Northern Idaho. USDA Forest Service Research Note INT-266.

Morales, B.J. 1987. Wood specific gravity in species from two tropical forests in Mexico. IAWA Bulletin n.s., 8(2): 143-148.

Morrell, J.J., Newbill, M.A. and Lonning, L.D. 1996. Sapwood thickness of Douglas-fir poles: implications for treatment of a changing resource. Proc. Amer. Wood Preserver's Assoc., 92: 193–204.

Moya, R. 2000. Behavior and performance in sawmilling logs of Terminalia amazonia of 6 years of age from the southern zone of Costa Rica. Cent. Am. For. J., 29: 14-19.

Moya, R. 2004. Wood of Gmelina arborea in Costa Rica. New Forest, 28: 299–307.

Moya, R. and Perez, D. 2008. Effect of physical and chemical soil properties on physical wood characteristics of Tectona grandis plantations in Costa Rica. J. Trop. For. Sci., 20: 147–155.

Moya, R., Leandro, L. and Murillo, O. 2009. Wood characteristics of three native species: *Terminalia amazonia, Vochysia guatemalensis* and *Hyeronima alchorneoides* growing in fast-growth plantations in Costa Rica. Revista Bosques, 30: 78–87.

Moya, M. and Munoz, F. 2010. Physical and mechanical properties of eight fast growing plantation species in Costa Rica. J. Trop. For. Sci., 22(3): 317–328.

Narayanamurti, D.1956. Composite Wood Timbers: Pterocarpus dalbergiodes-Padauk,Composite Wood, 3(4) :71-75.

Nelson, H.D. 1976. Gross influence on heartwood formation in black walnut and black cherry trees. USDA For. Res. Pap.FLP 268.

Ogata, K., Fujii, T., Abe, H. and Bass, P. 2008. Identifi cation of the timbers of Southeast Asia and the Western Pacific. Kaiseisha, Otsu, pp. 23-27.

Ohbayashi, H. and Shiokura, T. 1990. Wood anatomical characteristics and specific gravity of fast-growing tropical tree species in relation to growth rate. Mokuzai Gakkaishi, 36: 889–893.

Okuma, M. 1998. Wood utilization in the 21st century. Wood Industry, 52: 98-103.

Outer, R.W. and van Veenendaal, W.L.H. 1976. Variation in wood anatomy of species with a distribution covering both rainforest and savanna areas of the Ivory Coast, West Africa. In: Wood structure in biological and technological research (eds. P. Baas, A.J. Bolton and D.M. Catling). Leiden Bot. Sere, 3: 182-195.

Otebeye, G.O. and Kellison, R.C. 1980.Genetics of wood and bark characteristics of E. viminalis. Silv. Genet., 29: 27– 31.

Panshin, A.J. and Zeeuw, C.D. 1980. Textbook of wood technology: Structure, identification, properties, and uses of the commercial woods of the United States. McGraw-Hill, New York.

Panshin, A.J. and Zeeuw, C.D. 1980. Textbook of wood technology. McGraw-Hill Book Com-pany, New York. 722 pp.

Panshin, A. J., and Zeeuw, C.D. 1980. Textbook of wood technology. Ed. 3. Mc Graw-Hill, Inc., New York.

Panshin, A. J. and Zeeuw, C.D. 1980. Textbook of wood technology. 4th Ed. Mc Graw-Hill Publ. Comp., New York.

Parolin, P. and Ferreira, L.V. 1998. Are there differences in specific wood gravities between trees in varzea and igapo (Central Amazonia), Ecotropica, 4: 25- 32.

Pearson, R.G., Gilmore, R.C. 1971. Characterization of the strength of juvenile wood of loblolly pine (Pinus taeda L.). Forest Prod. J., 21(1):23-31.

Pentoney, R.E. 1953. Mechanisms affecting tangential vs. radial shrinkage. J. For. Prod. Res. Soc., 3: 27–32.

Perera, P.K.P and Amarasekera, H.S. 2003. Comparison of specific gravity variation in Swietenia macrophylla, Khaya senegalensis and Paulownia fortunei", Proceedings of the 9th annual Forestry & Environment Symposium (2004) organized by the University of Sri Jayewardenepura

Perera, P.K.P., Amarasekera, H.S. and Weerawardena, N.D.R. 2012. Effect of growth rate on wood specific gravity of three alternative timber species in Sri Lanka; *Swietenia macrophylla, Khaya senegalensis* and *Paulownia fortune.* J. Trop. Forest. Env., 2 (1): 26-35.

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

Perez, D., Kanninen, M., Matamoros, F., Fonseca, W. and Chaves, E. 2003. Heartwood, sapwood, and bark content of *Bombacopsis quinata* in Costa Rica. J. Trop. For. Sci., 16: 318–327.

Peszlen, I. 1994. Influence of age on selected anatomical properties of Populus clones. IAWA J., 15: 311–321.

Peszlen, I. 1998. Variation in specific gravity and mechanical properties of poplar clones. Drevarsky Vyskum, 43 (2): 1–17.

Plumptre, R.A. 1984. *Pinus caribaea* volume 2: Wood properties. Trap. For. Paper no. 11.Comm. For. Inst. Oxford.

Polge, 1969. Influence of the fertilization on the quality of wood of maritime pine. Ann. Sci. For., 26:45-64.

Pothier, D., Margolis, H.A. and Waring, R.H. 1989. Patterns of change of saturated sapwood permeability and sapwood conductance with stand development. Can. J. For. Res., 19: 432– 439.

Puritch, G.S. 1971. Water permeability of the wood of grand fir (Abies grandis (Dougl.) Lindl.) in relation to infestation by the balsam wooly aphid, Adelges piceae (Ratz.). J. Exp. Bot., 22: 936–945.

Putz, F.E., Coley, P.D., Lu, K., Montalvo, A. and Aiello, A. 1983. Uprooting and snapping of trees: structural determinants and ecological consequences. Can. J. For. Res., 13: 1011-1020.

Raczkowska, H.L. 1994. Variation of vessel lumen diameter in radial direction as an indication of the juvenile wood growth in oak (Quercus petraea Liebl.). Ann. Sci. For., 51:283–293.

Raczkowska, H.L. and Fabisiak, E. 1999. Radial variation of earlywood vessel lumen diameter as an indicator of the juvenile growth period in ash (Fraxinus excelsior L.). Holz Rohu.Werkstoff, 57: 283–286.

Rajput, S.S., Shukla, N.K. Gupta, V. K. and Jain, J.D. 1991. Timber mechanics: strength, classification and grading of timber. ICFRE No. 4, Indian Council of Forestry Research and Education, Dehra Dun. 192 pp.

Rao, R.V. and Hemavathi, T.R. 1992. The need to study reactionwood anatomy in plantation grown hardwood species. J. Timb. Dev. Assoc., 38: 30–34.

Raymond, C.A. and Muneri, A. 2001. Non-destructive sampling of *Eucalyptus globulus* and *Eucalyptus nitens* for wood properties. Wood Sci. Technol., 35: 27–39.

Raymond, C.A. 2002. Genetics of Eucalyptus wood properties. Ann. For. Sci., 59(5–6): 525–531.

Reid, R. 1995. Making Farm Trees Pay. The Role of Trees in Sustainable Agriculture. Workbook 2. Greening Australia Ltd, The Rural Industries Research and Development Corporation and the Land and Water Resources Research and Development Corporation, Canberra, Australia, 60 pp.

Ridoutt, B.G. and Sands, R. 1993. Within-tree variation in cambial anatomy and xylem cell dif-ferentiation in *Eucalyptus globulus*. Trees, 8: 18–22.

Ridoutt, B.G. and Sands, R. 1994. Quantification of the processes of secondary xylem fibre devel-opment in *Eucalyptus globulus* at two height levels. IAWA J., 15: 417–424.

Rocafort, J.E. 1973. The related and mechanical properties of big-leafed mahogany (Swietenia macrophylla King) from College, Laguna. Forpride Digest, 2: 46-47.

Rodan, B.D. and Blundell, A.G. 2003. Can sustainable mahogany stem from CITES Science. Bioscience, 53(7): 619.

Rudman, P. 1970.The influence of genotype and environment on wood properties of juvenile Eucalyptus camaldulensis. Silvae Genet., 19: 49-53.

Ryan, M.G., Gower, S.T., Hubbard, R.M., Waring, R.H., Gholz, H.L., Cropper, W.P. and Running, S.W. 1995. Woody tissue maintenance respiration of four conifers in contrasting climates. Oecologia, 101: 133-140.

Sahri, M.H., Ashaari, Z., Kaderl, R.A. and Mohmod, A.L. 1998. Physical And Mechanical Properties of Acacia mangium and Acacia auriculiformis from Different Provenances. J. Trap. Agric. Sci., 21(2): 73 – 81.

Sakagami, H., Matsumura, J. and Oda, K. 2007. Shrinkage of tracheid cells with desorption visualized by confocal laser scanning microscopy. IAWA J., 28 (1): 29–37.

Saldarriaga, J.G. 1987. Recovery following shifting cultivation: A century of succession in the Upper Rio Negro. In: C.F. Jordan (ed.), Amazonian rain forests. Ecosystem disturbance and recovery: 24–32. Springer, New York, Berlin.

Sandercock, C.F., Sands, R., Ridoutt, B.G., Wilson, L.F. and Hudson, I.1995. Factors determining wood microstructure in Eucalyptus. In: B.M. Potts, Borralho, N.M.G., Reid, J.B. Cromer, R.N. Tibbits, W.N. and Raymond, C.A. (eds.), Eucalypt plantations: improving fibre yield and quality: CRC for Temperate Hardwood Forestry, Hobart, pp. 5–9.

Saranpaa, P. 2003. Wood density and growth. In: J.R. Barnett and G. Jeronimidis (eds.), Wood quality and its biological basis: Blackwell and CRC Press, London and Boca Raton, FL. Biological Sciences Series, pp. 87–117

Schmitz, N., Verheyden, A., Beeckman, H., Kairo, J.G. and Koedam, N. 2006. Influence of a salinity gradient on the vessel characters of the mangrove species *Rhizophora mucronata* Lam. Ann. Bot., 98:1321–1330.

Schniewind, A.P. and Gammon, B.W. 1983. Strength and related properties of knobcone pine. Wood Fiber Sci., 15(1): 2-7.

Scott, C.W. and Mac Gregor, W.D. 1952. Fast grown wood, its features, and value with special reference to conifer planting in the United Kingdom since 1919. 6th British Commonwealth For Conf Canada, 20pp.

Searle, S.D. 2000. Acacia melanoxylon-a review of variation among planted trees. Aust. Forest., 63: 79-85.

Searle, S.D. and Owen, J.V. 2005. Variation in basic wood density and percentage heartwood in temperate Australian Acacia species. Aust. Forest., 68:126-136.

Sedenio, P.E. 1991. Influence o f growth rate on specific gravity, fibre length and cell wall thickness of an evenaged mahogany stand (Swietenia macrophylla King).CMU J . Sci. 4 : 22.

Sellin, A. 1996. Sapwood amount in Picea abies (L.) Karst determined by tree age and radial growth rate. Holzforschung, 50(4): 291–296.

Sekhar, A.C. 1967. Some Indian Timbers Equivalent to Foreign Timbers,Van Vigyan, 5(1-2):18-24.

Sekhar, A.C. 1988. Physical properties of Indian timbers. In: Ranganathan, V., Bakshi, B.K., Purshotham, A., Krishnamoorthy, A. and Sekhar, A.C. (eds.). Hand book on Indian Woods and Wood panels: Solid Woods. Oxford University Press, Delhi, pp.70-83.

Sekar, A.C. and Rawat, B.S. 1959. Studies on the effect of specific gravity on strength consideration of Indian timbers. J. Inst. Eng., 39(8): 865-870.

Semple, K. and Evans, P.D. 2000. Adverse effects of heartwood on the mechanical properties of wood-wool-cement board manufactured from radiate pine. Wood Fibre Sci., 32:37-43.

Shanavas, A. and Kumar, B.M. 2006. Physical and mechanical properties of three agroforestry tree species from Kerala, India. J. Trop. Agric., 44 (1-2): 23-30.

Sharma, S.K., Rao, R.V., Shukla, S.R., Kumar, P., Sudheendra, R., Sujatha, M. and Dubey, Y.M. 2005. Wood quality of coppiced Eucalyptus tereticornis for value addition. IAWA J., 26: 137–147.

Shelburne, V.B., Hedden, R.L. and Allen, R.M. 1993. The effects of site, stand density, and sapwood permeability on the relationship between leaf area and sapwood area in loblolly pine (Pinus taeda L.). For. Ecol. Manage., 58:193–209.

Shepard, R.K., Shottafer, J.E. 1992. Specific gravity and mechanical property-age relationship in red pine. Forest Prod. J., 42: 60-66.

Shukla, N.K., Rajput, S.S. and Lal, M. 1989. Some studies on variation of strength along tree height in Eucalyptus. J. Ind. Acad. Wood Sci., 20: 31-36.

Shukla, N.K. and Rajput, S.S. 1990. Relationships of ultimate bending and compressive strength with different mechanical properties. J. Ind. Acad. Wood Sci., 21(1): 1-2.

Shukla, N.K., Rajput, S.S., Lal, M. and Khanduri, A.K. 1994. Studies on the variation of strength along the tree height in Eucalyptus hybrid from Punjab. J.Timb.Dev.Assoc., 40: 27-31.

Shukla, S.R., Sudheendra, R. and Rao R.V.1999. Preliminary studies on physical and mechanical properties of plantation grown Andaman padauk

(Pterocarpus dalbergioides) from Karnataka. J. Timb. Dev. Assoc., 45 (1-2): 1 –15.

Sluder, E.R.1970. Variation in wood specific gravity of yellow poplar (Liriodendron tulipifera) and its relationship to environment conditions in the southern Appalachians . PhD Thesis North Carolina State Univ Raleigh, North Carolina, 77pp.

Sluder, E.R.1972. Variation in specific gravity of yellow-poplar in the southern Appalachians. Wood Sci., 5: 132-138.

Smith, J.H.G. 1971. Specific gravity and fiber length of hybrid poplar. J. Forest., 69: 34-35.

Soerianegara, I., 1994. Plant resources of South-East Asia 5(1): Timber trees: major commercial timbers. Prosea, Bogor,141p.

Sokal, R.R. and Rohlf, F.J. 2001. Biometry. Freeman, New York.

Skolman, R.G. 1972. Specific gravity variation in Eucalyptus robusta grown in Hawaii, U.S Forest Service Research Paper PSW-78, 7 pp.

Spicer, R. and Gartner, B.L. 1998. Hydraulic properties of Doughlas-fir (Pseudotsuga menziesii) branch halves with reference to compression wood. Tree Physiol., 18: 777-784.

Spicer, R. and Gartner, B.L. 2001. The effects of cambial age and position within the stem on specific conductivity in Doughlas-fir (Pseudotsuga menziesii) sapwood. Trees, 15: 222-229.

Stringer, J.W. and Olson, J.R. 1987. Radial and vertical variation in stem properties of juvenile black locust (*Robinia pseudoacacia*). Wood Fibre Length, 19(1):59–67

Talbert, J.T. and Jett, J.B. 1981. Regional specific gravity values for plantation grown loblolly pine in the southeastern United States. For. Sci., 27:801-807.

Taylor, F.W. 1973. Variations in the anatomical properties of South African grown Eucalyptus grandis. Appita., 27: 171–178.

Taylor, F.W. and Wooten, T.E. 1973. Wood property variation of Mississippi Delta hardwoods. Wood and Fiber Sci., 5: 2–13.

Taylor, A.M., Gartner, B.L. and Morrell, J.J. 2002. Heartwood formation and natural durability – a review. Wood and Fiber Sci., 34: 587-611.

Thompson, D.C. 1989. The effect of stand structure and stand density on the leaf area sapwood relationship of lodge pole pine. Can. J. For. Res., 19: 392–396.

Thor, E. 1961. Variation patterns in natural stands of Loblolly pine. 6th South.Conf. For. Tree Impr., Gainesville, Fl. pp.25-44.

Thulasidas, P.K. and Bhat, K.M. 2009. Log Characteristics and Sawn Timber Recovery of Home-Garden Teak from Wet and Dry Localities of Kerala, India Small scale Forestry, 8(1):15-24.

Tjoelker, W. 1990. Specific gravity sorting raises kiln drying efficiency. Forest Industries, p. 34 -36.

Todorovsky, S. 1966. Effect of certain factors on the proportion of sapwood and heart wood in the stem of Pinus sylvestris and Pinus nigra. Summary from For. Abstr. 1968. No. 2908.

Tognetti, R., Longobucco, A. and Raschi, A. 1998. Vulnerability of Xylem to embolism in relation to plant hydraulic resistance in Quercus pubescens and Quercus ilex co-occurring in a Mediteranean coppice stand in central Italy. New phytol., 139: 437-447.

Tsoumis, G. 1991. Science and technology of wood: Structure, properties, utilization. Van Nostrand Reinhold, New York.

Tsuchiya, R. and Furukawa, I. 2008. The relationship between radial variation of wood fiber length, vessel lumen diameter and the stage of diameter growth in Castanea crenata. Mokuzai Gakkaishi, 54: 116–122

Tsuchiya, R. and Furukawa, I. 2009. Radial variation in the size of axial elements in relation to stem increment in *Quercus serrata.* IAWA J., 30: 15–26.

Tu Kim, N., Ochiishi, M., Matsumura, J. and Oda, K. 2008. Variation in wood properties of six natural acacia hybrid clones in northern Vietnam. J. Wood Sci., 54:436–442.

Tyree, M.T. and Ewers, F.W. 1991. The hydraulic architecture of trees and other woody plants. New Phytologist, 119: 345-360.

Tyree, M.T., Davis, S.D. and Cochard, H. 1994. Biophysical perspectives of xylem evolution : is there a trade off of hydraulic efficiency for vulnerability to dysfunction. IAWA J., 15: 335-360.

Valente, C.A., de Sousa, A.M., Furtado, F.P., de Carvalho, A.P. 1992. Improvement program for Eucalyptus globulus at PORTUCEL: Technological component. Appita., 45: 403–407.

van Buijtenen, J.P. 1982. Fibre for the future. Tappi., 65(8):10-12.

van Eck, W.A. and Woessner, R.A. 1964. A study of wood density in yellow poplar and red oak as related to environment. West Virginia Acad Sci, 8pp.

Villagra, P.E. and Junent, R.F.A. 1997. Wood structure of Prosopis alpataco and P. argentina growing under different edaphic conditions. IAWA J., 18: 37-51.

Vrolijk, K.G.M.C., Jutte, S.M. and Hof, T. 1962. Properties of New Guinea woods. Nova Guinea Bot., 10:137–175.

Walt, V.J.J.A., Werker, E. and Fahn, A. 1988. Wood anatomy of the Pelargouium (Geraniaeae). IAWA Bull. n.s., 10:201- 207.

Walker, J.C.F. 2006. Primary wood processing: principles and prac-tice. Springer, Dordrecht, Netherlands.

Wang, S., Little, R.C. and Rockwood, D.L.1984. Variation in density and moisture content of wood and bark among twenty Eucalyptus grandis progenies. Wood Sci.Technol., 18: 97–102.

Wate, P.A., Chamshama, S.A.O. and Mugasha, A.G. 1999. The survival, growth and wood basic densities of 14 year old Eucalyptus camaldulensis at Michafutene, Mozambique. South Afr. For. J., 186: 19–27.

Watson, F. 1996. A view from the forest floor: the impact of logging on indigenous peoples in Brazil. Botanical Journal of the Linnean Society, 122: 75-87.

Webb, C.D. 1964. Natural variation in specific gravity, fibre length and interlocked grain of sweetgum (Liquidambar styraciflus) in the south

Atlantic states. PhD Thesis School For North Carolina State Univ Raleigh, North Carolina, 125pp.

Wellwood, R.W. 1955. Sapwood-heartwood relationships in second-growth Douglas-fir. For. Prod. J., 5: 108-111.

Wellwood, R.W. and P.E. Jurazs. 1968. Vari-ationin sapwood thickness, specific grav-ity and tracheid length in western red cedar. For. Prod. J., 18: 37-46.

Wheeler, E.A., McClammer, J. and LaPasha, C.A. 1995. Similarities and differences in dicotyle-donous woods of the Cretaceous and Paleocene San Juan Basin, New Mexico, USA. IAWA J., 16: 223–254.

Whitehead, D., Edwards, W.R.N. and Jarvis, P.G. 1984. Conducting sapwood area, foliage, and permeability in mature trees of Picea sitchensis and Pinus contorta. Can. J. For. Res., 14:940–947.

Wiemann, M.C. and Williamson, G.B. 1988. Extreme radial changes in wood specific gravity in some tropical pioneers. Wood Fiber Sci., 20: 344- 349.

Wiemann, M. C. and Williamson, G.B. 1989. Wood specific gravity gradients in tropical dry and montane rain forest trees. Amer. J. Bot., 76: 924– 928.

Wilkes, J. 1984. The influence of rate of growth on density and heartwood extractives content of eucalypt species. Wood Sci. Technol., 18: 113–120.

Wilkins, A.P. and Papassotiriou, S.1989. Wood anatomical variation of Acacia melauoxylon in relation to latitude. IAWA Bull. n.s., 10: 201-207.

Wilkins, A.P. 1991. Sapwood, heartwood and bark thickness of silvicultural treated Eucalyptus grandis. Wood Sci. Technol., 25:415–423.

Williams, M.D. 1994. Chemi mechanical pulps from plantation eucalypts. Appita J., 47:137-142.

Wilson, L., Hudson, I. and Beveren, V.K. 1997. Vessel distribution at two percentage heights from pith to bark in a 7 year old Eucalyptus globulus tree . Appita J., 50: 495-500.

Woeste, K.E. 2002. Heartwood production in a 35-year-old black walnut progeny test. Can. J. For. Res., 32(1):177–181.

Woodcock, D.W. 2000. Wood specific gravity of trees and forest types in the Southern Peru-vian Amazon. Acta Amazonica, 30: 589–599.

Woodcock, D.W. and Shier, A.D. 2002. Wood specific gravity and its radial variations: the many ways to make a tree. Trees, Structure and Function, 16(6): 437-443.

Yang, K.C., Murchison, H.G. 1992. Sapwood thickness in Pinus contorta var. latifolia . Can. J. For. Res., 22:2004–2006.

Yang, K.C., Hazenberg, G., Bradfield, G.E. and Maze, I.R. 1985. Vertical variation of sapwood thickness in Pinus banksiana Lamb. and Larix laricina(Du Roi) K. Koch. Can. J. For. Res., pp. 822-828.

Yanchuk, A.D., Dancik, B.P. and Micko, M.M. 1983.Intraclonal variation in wood density of trembling aspen in Albena. Wood Fiber Sci., 15: 381-394.

Yanchuk, A.D., Dancik, B.P. and Micko, M.M. 1984. Variation and heritability of wood density and fibre length of trembling aspen in Albena, Canada. Genet., 33:11-16.

Yanchuk, A.D. and Micko, M.M.1990. Radial variation of wood density and fibre length in Trembling aspen .IAWA Bulletin n.s., 11 (2): 211-215.

Yeatman, C.W. 1967. Biogeography of Jackpine. Can. J. Bot., 45: 2201-2211.

Yoshihara, H. and Fukuda, A. 1998. Influence of loading point on the static bending test of wood. J. Wood Sci., 44:473-481.

Zhang, X.L., Deng, L. Baas, P. 1988. The ecological wood anatomy of the Lilac (Syringa oblata var. giraldii) on Mount Taibei in northwestern China. IAWA Bull. n.s., 9: 24-30.

Zhang, S.Y. 1992. Structure-property relationship of wood in East- Liaoning oak. Wood Sci. Technol., 26: 139-149.

Zhang, S.Y. 1995. Effect of growth rate on wood specific gravity and selected mechanical properties in individual species from distinct wood categories. Wood Sci. Technol., 29(6): 451–465.

Zhang, S. Y. 1997. Wood specific gravity-mechanical relationship at species level Wood Sci. Technol., 31: 181-191.

Zhang, S.Y., Gosselin, R. and Chauret, G. 1997.Timber management toward wood quality and end product value. Proc. Of CTIA/IUFRO international wood quality workshop, Quebec, 500p.

Zimmermann, M.H. 1978. Structural requirements for optimal conduction in tree stems. In: Tomlinson, P.B. and Zimmermann (eds.), M.H.Tropical trees as living systems: S17-532. Cambridge Univ, Press, London, New York. Melbourne.

Zimmermann, M.H.1983. Xylem structure and the ascent of sap. Springer-Verlag, Berlin.

Zobel, B.J. 1984. The changing quality of the world wood supply. Wood Sci. Technol., 18:1-17.

Zobel, B.J. and Jett J.B. 1985. Genetics of Wood Production. Springer-Verlag, Berlin, Heidelberg, NewYork, USA, 337 p.

Zobel, B.J., Matthias, M., Roberds, J.H. and Kellison, R.C.1968. Moisture content of southern pine trees, Tech. Rep.37, School For. Res., N. C. State Uni., Raleigh, N.C.

Zobel, B.J. and Talbert, J. 1984. Applied forest tree improvement. Wilely, New York, 511pp.

Zobel, B.J. van Wyk, G. and Stahl, P. 1987. Growing exotic forests. Wiley, New York, 505p.

Zobel, B.J. and van Buijtenen, J.P. 1989. Wood variation, its causes and control. Springer-Verlag, Berlin, Heidelberg, New York, 363 p.

Zobel, B.J. and Jett, J.B. 1995. Genetics of Wood Production. Berlin, Springer-Verlag.

Zobel, B.J. and Sprague, J.R. 1998. Juvenile wood in forest trees. Berlin: Springer- Verlag.

Summary

SUMMARY

The present investigation on the "Wood quality evaluation of tree species raised in research trials of the Kerala forest department at various localities" was carried out in College of forestry, Vellanikkara during 2010-2012. The results are summarised below:

1. Species variation in moisture content (green to oven dry) between *Pterocarpus dalbergioides, Swietenia macrophylla* and *Pericopsis mooniana* showed significant difference, whereas radial variation within species was non- significant. *P. mooniana* showed highest species average followed by *S. macrophylla* and *P. dalbergioides*

2. Variation between species as well as radial variation within trees among all species was found to be non-significant with regard to the moisture content (air dry to oven dry). Species average with regard to moisture content was higher in *S. macrophylla,* followed by *P.dalbergioides* and *P. mooniana.*

3. Specific gravity (fresh weight) differed significantly at one percent level between species. *P. mooniana* accounted for the highest species average for green specific gravity followed by *S. macrophylla* and *P. dalbergioides.* Variation between positions within species was found to be non-significant at five percent level

4. Between species difference was significant between *P. dalbergioides, S. macrophylla* and *Pericopsis mooniana* with regard to the specific gravity (air dry to oven dry). *Pericopsis mooniana* showed the highest value for air dry specific gravity followed by *S. macrophylla* and *P. mooniana.* Significant variation in air dry specific gravity existed along the radial positions among the three species under study. *S. macrophylla* and *Pterocarpus dalbergioides* showed an increasing trend in air dry specific gravity towards middle, whereas *P. mooniana* was found to have an increasing trend towards pith and periphery from the middle position.

5. Between species difference with regard to oven dry specific gravity was significant among *P. dalbergioides, S. macrophylla and Pericopsis mooniana. Pericopsis mooniana* showed the highest value for oven dry specific gravity and was significantly differed from the other two species. Significant variation in oven dry specific gravity existed along the radial positions among the three species under study.

6. Radial shrinkage variation at green condition was significant between species, whereas, radial variation within species was non- significant. Species averages were found to be higher in *P. mooniana* followed by *P. dalbergioides* and *S. macrophylla.* With regard to radial variation, *P. dalbergioides* showed a decreasing trend from pith towards periphery. *S. macrophylla* showed an increasing trend towards middle from the pith region and thereafter decreased towards periphery. *P. mooniana* first showed decline from pith towards middle and then showed an increasing trend towards periphery.

7. Between species variations with respect to radial shrinkage (air dry to oven dry) differed significantly among the three species under study. *S. macrophylla* was found to have the highest value followed by *P. mooniana* and *P. dalbergioides.* Within tree radial variation was found to be non-significant. *P. dalbergioides* showed a decreasing trend from pith towards middle which increased towards periphery position. *S .macrophylla* showed a reverse trend of increasing radial shrinkage values from pith towards middle which decreasing trend towards periphery position. *P. mooniana* showed a decreasing trend from pith to middle and thereafter it showed a slight increase towards periphery.

8. Between species variation among different species as well as within species variation was significant with regard to radial shrinkage (green to oven dry). *S. macrophylla* showed the highest value followed by *P. mooniana* and *P. dalbergioides.* Regarding radial variation within species, there was a decreasing trend from pith to middle. Thereafter it was found to increase towards periphery in the case of *P. dalbergioides,* whereas *S. macrophylla* showed a reverse trend of increasing radial shrinkage from pith towards middle and thereafter it declined towards periphery.

9. Analysis of result, pertaining to tangential shrinkage (green to air dry) revealed that significant difference existed between species, whereas radial variation within species was found to be non -significant. *S. macrophylla* had maximum shrinkage followed by *P. mooniana* and *P. dalbergioides.* Radial variation in *P. dalbergioides* showed decreasing trend from the pith towards the middle position which thereafter will found

to increase towards periphery. Similarly, *S. macrophylla* showed the same pattern of reduction in tangential shrinkage (green to air dry) from pith towards middle and thereafter increased towards periphery.

10. Tangential shrinkage (air dry to oven dry) in *P. dalbergioides*, *S. macrophylla* and *P. mooniana* revealed that between species variation as well as within tree radial variation among the three species under study were significant at one percent level. *P. dalbergioides* had the lowest value. *P. mooniana* and *S. macrophylla* were found to have similar values. Periphery position showed the highest value in *P. dalbergioides*. *S. macrophylla* showed similar values for pith, middle and periphery positions. *P. mooniana* showed higher value the pith, followed by periphery and middle position.

11. Variation in tangential shrinkage (green to oven dry) between species as well as radial variation within species was found to be significant at one percent and five percent level respectively. *P. mooniana* had the highest value whereas *S. macrophylla* and *P. dalbergioides* were at par. In the case of *P. dalbergioides*, there was a decreasing trend in tangential shrinkage from pith towards middle which thereafter was found to increase towards periphery. There was a decreasing trend from pith towards the middle region which showed a slight increase towards periphery thereafter in the case of *P. mooniana*.

11. Variation in heartwood percentage between species was significant at one percent level. *S. macrophylla* showed the highest value followed by *P. mooniana* and *P. dalbergioides*.

12. Analysis of bark thickness revealed that between species difference was significant among *P. dalbergioides, S. macrophylla and Pericopsis mooniana. P. dalbergioides* showed the highest value for bark thickness followed by *S. macrophylla* and *P. mooniana*.

13. With regard to log volume *Swietenia macrophylla* showed the highest value followed by *P. mooniana* and *P. dalbergioides*. Sawn wood recovery rate was highest in P. *mooniana*, followed by *S. macrophylla* and *P. dalbergioides*.

14. Variation in vessel area between species as well as between radial positions within species were significant (at 1% level). Highest species average in vessel area was found in *Pterocarpus dalbergioides* followed by *Swietenia macrophylla* and *Pericopsis mooniana*. Periphery position showed the highest value for vessel diameter than pith and middle position and a decreasing trend in vessel area from periphery to pith in all the three species.

15. *Pterocarpus dalbergioides* showed an increasing trend in vessel diameter from periphery towards pith position whereas, vessel diameter in the middle and pith positions in *Swietenia macrophylla* was found to be similar to periphery position. *Pericopsis mooniana* did not show any significant difference between radial positions for this property.

16. Significant variation existed between species with regard to vessel frequency at one percent level whereas, radial variation within species did not differ significantly for vessel frequency. *P. dalbergioides* showed a decreasing trend from the pith towards middle and thereafter increased towards periphery region. Both *P. mooniana* and *S. macrophylla* showed the same trend of variation with regard to vessel frequency.

17. Between species as well as radial variation within species differed significantly. Highest species average was found in *P. mooniana* followed by *P. dalbergioides* and *S. macrophylla*. In the case of *Pterocarpus dalbergioides* pith and periphery position differed significantly between each other, whereas middle position was found to be at par with pith and periphery positions. Higher value for vessel length was found in the periphery position in *Pterocarpus dalbergioides*. *Swietenia macrophylla* and *P. mooniana* did not show significant difference between the pith, middle and periphery positions.

18. Significant difference existed between species for ray height whereas, radial variation within species was found to be non-significant. Highest species average was found in *Swietenia macrophylla* followed by *Pericopsis mooniana* and *Pterocarpus dabergioides* .The latter two species showed homogeneous values.

19. Ray width showed highly significant variation between species as well as between radial positions within species. Highest species average was noticed in *S. macrophylla* followed by *Pericopsis mooniana* and *Pterocarpus dalbergioides. Pterocarpus dalbergioides* and *Pericopsis mooniana* were homologous for pith, middle and periphery. In the case of *Swietenia marophylla* showed significant difference in the periphery region compared to middle and pith position.

20. Variation between species and radial variation within species with regard to ray frequency were significant. Highest species average was found in *P. dalbergioides* followed by *P. mooniana* and *S. macrophylla.*

21. Species averages in fibre length differed significantly at one percent level whereas radial variation within species was non-significant. *P. mooniana* showed the highest value followed by *S. macrophylla* and *P. dalbergioides. P. dalbergioides* showed an increasing trend from the pith towards periphery position. *S. macrophylla* showed decreasing trend from pith to middle and then showed an increasing trend from middle to periphery position. In the case of *P. mooniana,* decreasing trend was observed from pith towards periphery.

22. Between species comparison showed that species averages for fibre wall thickness as well as radial variation within species were found to be non-significant among each other. Higher value for fibre wall thickness was found in *S. macrophylla* whereas *P.dalbergioides* and *P. mooniana* showed same value. *P. dalbergioides* showed an increase in value from pith to middle, and then showed a decrease in value towards periphery. *S. macrophylla* showed an increase in value from pith to middle and later showed a decline towards periphery. *P. mooniana* showed a different pattern of variation with a decreasing value from pith to middle, and then showed an increase towards periphery.

23. Analysis of variance revealed that between species differed significantly (1% level) with respect to fibre lumen diameter whereas radial variation within species under study were found to be non-significant to each other. *P. dalbergioides* showed the highest value for fibre lumen diameter, followed by *S. macrophylla* and *P. mooniana. P. dalbergioides* showed a decreasing trend from the pith towards periphery region. *S.*

macrophylla showed an initial increase of fibre lumen diameter from pith to middle and then showed a decline from middle to periphery position. In the case of *P. mooniana,* decreasing trend was observed from pith to the periphery which later showed an increasing trend towards periphery.

24. Between species variation was significant with respect to fibre lumen diameter and radial variation within species were found to be non-significant. Species averages for fibre lumen diameter were found to be similar in *P. dalbergioides* and *S. macrophylla,* whereas *P. mooniana* significantly different from the above two species for fibre lumen diameter. All the three species showed a decreasing trend from pith towards periphery position.

25. Variation between tree species in ray percent for *Pterocarpus dalbergioides, Swietenia macrophylla* and *Pericopsis mooniana* as well as within tree variation were found to be significant at one percent level. S. *macrophylla* showed the highest value followed by *P. mooniana* and P. *dalbergioides.*

26. No significant difference existed in vessel percent between species as well as between positions within species among the different species under study. *S. macrophylla* showed the highest species average followed by *P. mooniana* and S. *macrophylla. P. dalbergioides* showed an increasing trend towards middle from pith and thereafter was found to increase towards the periphery position. *P. mooniana* showed the same pattern of increasing trend towards middle from pith and later a declining trend towards periphery position. *S. macrophylla* was found to have a decreasing trend from pith towards periphery.

27. Variation in species average with regard to parenchyma percent between species was significant whereas, radial variation was found to be non-significant. Highest species average in parenchyma percent was found in *P. mooniana,* followed by *S. macrophylla* and *P. dalbergioides. P. dalbergioides* showed increasing parenchyma percent from the pith towards middle, which thereafter showed a decreasing trend towards periphery.

28. Fibre percent was significantly different between the three tree species. *P. dalbergioides* showed highly significant difference followed by *S. macrophylla* and *P. mooniana*. Radial variation in fibre percent within species was non-significant.

29. Compressive stress at limit of proportionality at green and air dry condition for compressive strength perpendicular to the grain test were found to be higher in *Pericopsis mooniana* followed by *S. macrophylla* and *P. dalbergioides*. When compared with teak, the CS at LP value was higher in *P. mooniana* where as *P. dalbergioides* and *S. macrophylla* showed a lower value for CS at LP.

30. CS at 2.5 mm deflection in compressive strength perpendicular to the grain test showed significant difference between species at green and air dry condition. Higher value was found in *P. mooniana* followed by *S. macrophylla* and *P. dalbergioides* which were at par.

31. Variation in modulus of elasticity (MOE) among species was significant at green and air dry condition in compressive strength perpendicular to the grain test. *P. mooniana* showed highest value followed by *S. macrophylla* and *P. dalbergioides*.

32. CS at LP in compression parallel to grain test at green condition and air dry condition showed significant difference between the different species. *P. mooniana* showed the highest value followed by *P. dalbergioides* and *S. macrophylla* .CS at LP value for *P. mooniana* was higher than teak whereas the latter two species showed values which were lower than that of teak

33. CS at ML in compression parallel to grain test at green and air dry condition were significantly differ among *P. dalbergioides, S. macrophylla* and *P. mooniana*. *Pericopsis mooniana* followed by *S. macrophylla* and *P. dalbergioides.*

34. Values for MOE in compression parallel to grain test at green and air dry condition were found to be significant among all the species under study. *P.mooniana* showed significantly higher value followed by *P. dalbergioides* and *S. macrophylla*. All the species showed lower MOE value when compared to teak.

35. Modulus of rupture in static bending test at green condition and air dry condition in *P. mooniana* was higher followed by *P. dalbergioides* and *S. macrophylla.* Its value was found to be higher than that of teak (841) as reported by Sekhar (1988). MOR values in *S. macrophylla* and *P. dalbergioides* were found to be lower than teak.

36. Maximum load sustained by all the three species were lower than the maximum load reported for teak at green and air dry condition in the static bending test. Among the three species, *P. mooniana* showed the highest value followed by *P. dalbergioides* and *S. macrophylla.*

37. HS at ML at green and air dry condition in the static bending test was higher in *P.mooniana* followed by *P. dalbergioides* and *S. macrophylla.*

38. HS at LP at green and air dry condition in the static bending test was higher in *P. mooniana* followed by *P. dalbergioides* and *S. macrophylla* .

39. FS at LP at green and air dry condition in the static bending test was higher in *P. mooniana* followed by *P.dalbergioides* and *S. macrophylla.*

40. *P. mooniana* showed highest values for MOE at green and air dry condition in the static bending test followed *P. dalbergioides and S. macrophylla.* All the three species showed lower value when compared to teak.

41. In the case of *P. dalbergioides* parenchyma percentage was negatively correlated with the horizontal shear stress at maximum load in air dry condition in static bending tests and positively correlated with crushing strength at limit of proportionality in compression strength perpendicular to grain at green condition. Correlation of specific gravity with anatomical characters shows that vessel diameter, vessel length and fibre length are significantly correlated with specific characters.

42. In the case of *Swietenia macrophylla* , vessel diameter was positively correlated with the horizontal shear stress at maximum load, whereas it was found to be negatively correlated with fibre stress at limit of proportionality at dry condition in static bending

test. Oven dry specific gravity showed positive correlation with CS at ML in compression parallel to grain at dry condition. With respect to static bending test, oven dry specific gravity was found to be positively correlated with HS at LP and FS at LP in green condition. Fibre percent showed negative correlation with MOE at green condition in the static bending test. None of the anatomical characters were correlated with specific gravity.

43. In the case of *P. mooniana,* ray height was found to have negative correlations with CS at LP and CS at 2.5 mm deflection at green condition and modulus of elasticity at dry condition in compression perpendicular to grain test. Vessel diameter and ray width were found to have positive correlation with modulus of elasticity at dry condition in compression parallel to grain. Vessel length showed significant correlation with CS at ML at dry condition in compression parallel to grain. Fibre lumen diameter was positively correlated with MOR (green and air dry condition), ML (green condition), HS at ML (green condition) and HS at LP (green condition). Fibre length showed positive correlation with MOE (air dry).

44. Linear and quadratic models were developed to show the dependence of specific gravity on anatomical properties. In the case of *P. dalbergioides* correlation of specific gravity with vessel diameter was depicted through a quadratic equation whereas correlation of specific gravity with vessel length and fibre length were given through linear equation. No correlation was observed in *S. macrophylla* in the specific gravity-anatomical property relationships.

APPENDIX

I. ANOVA for comparing moisture content (green to oven dry) between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	5415.70	2707.85	7.84**
Radial position within species	6	3184.28	530.71	1.54^{ns}
Error	33	11400.08	345.46	
Total	44	20000.06		

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

II. ANOVA for comparing moisture content (air dry to oven dry) between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	666.50	333.25	2.92^{ns}
Radial position within Species	6	444.26	74.04	0.65^{ns}
Error	33	3767.48	114.17	
Total	41			

ns- non significant at 0.05 level

III. ANOVA for comparing specific gravity at green condition between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	1.25	0.62	34.91**
Radial position within species	6	0.19	0.03	1.78^{ns}
Error	33	0.59	0.02	
Total	41			

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

IV. ANOVA for comparing air dry specific gravity between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	0.30	0.15	23.39**
Radial position within species	6	0.22	0.04	5.71**
Error	33	0.21	0.01	
Total	41	0.74		

** *significant at 0.01 level*

V. ANOVA for comparing oven dry specific gravity between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	0.55	0.27	71.57**
Radial position within species	6	0.14	0.02	6.30**
Error	33	0.13	0.004	
Total	41			

** *significant at 0.01 level*

VI ANOVA for comparing radial shrinkage green to air dry between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	17.05	8.52	49.93**
Radial position within species	6	0.85	0.14	0.830^{ns}
Error	30	5.12	0.17	
Total	38	23.02		

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

VII. ANOVA for comparing radial shrinkage (air dry to oven dry) between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	9.09	4.55	20.54**
Radial position within species	6	4.34	0.72	3.26^{ns}
Error	30	6.64	0.22	
Total	38	20.07		

ns non significant at 0.05 level

VIII. ANOVA for comparing radial shrinkage green to oven dry between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	5.32	2.66	12.61**
Radial position within species	6	3.96	0.66	3.13*
Error	30	6.32	0.21	
Total	38	15.61		

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

IX. ANOVA for comparing the tangential shrinkage (green to air dry) between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	112.49	56.24	453.60**
Radial position within species	6	0.16	0.03	0.21^{ns}
Error	30	3.72	0.12	
Total	38	116.37		

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

X. ANOVA for comparing tangential shrinkage air to oven dry between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	6.29	3.15	8.53**
Radial position within Species	6	8.53	1.42	3.85**
Error	30	11.07	0.37	
Total	38	25.89		

** *significant at 0.01 level;*

XI. ANOVA for comparing tangential shrinkage green to oven dry between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	5.61	1.24	3.94**
Radial position within Species	6	2.48	0.93	2.97*
Error	30	9.44	0.31	
Total	38	17.53		

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

XII. ANOVA for comparing vessel area between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	8846018574	4423009287	59.93**
Radial position within species	6	5609534871	934922479	12.67**
Error	30	2214068399	73802280	
Total	38	16669621844		

** *significant at 0.01 level*

XIII. ANOVA for comparing vessel diameter between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	54937.31	27468.66	66.47**
Radial position within Species	6	46379.40	7729.90	18.71**
Error	30	12396.71	413.22	
Total	38	113713.42		

*** significant at 0.01 level*

XIV. ANOVA for comparing vessel frequency between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	172.15	86.07	103.62**
Radial position within Species	6	11.73	1.95	2.35^{ns}
Error	30	24.92	0.83	
Total	38			

ns non significant at 0.05 level

XV. Results of ANOVA for comparing vessel length between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	10631.56	5315.78	10.25**
Radial position within species	6	7814.85	1302.47	2.51*
Error	30	15556.55	518.55	
Total	38			

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

XVI. ANOVA for comparing ray height between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	832938.12	416469.06	220.82**
Radial position within species	6	19123.78	3187.30	1.69^{ns}
Error	30	56580.59	1886.02	
Total	38			

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

XVII. Results of ANOVA for comparing ray width between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	27265.17	13632.59	178.06**
Radial position within species	6	3349.82	558.30	7.29**
Error	30	2296.83	76.56	
Total	38			

*** significant at 0.01 level;*

XVIII. ANOVA for comparing ray frequency between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	1377.07	688.54	35.93**
Radial position within species	6	317.35	52.89	2.76*
Error	30	574.91	19.16	
Total	38			

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

XIX. ANOVA for comparing vessel frequency between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	172.15	86.07	103.62**
Radial position within species	6	11.73	1.95	2.35^{ns}
Error	30	24.92	0.83	
Total	38			

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

XX. ANOVA for comparing fibre length between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	904248.40	452124.20	17.67**
Radial position within species	6	186850.50	31141.75	1.22^{ns}
Error	30	767633.05	25587.77	
Total	38			

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

XXI ANOVA for comparing fibre wall thickness between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	0.51	0.25	0.05^{ns}
Radial position within species	6	23.20	3.87	0.74^{ns}
Error	30	156.03	5.20	
Total	38			

ns - significant at 0.05 level

XXII. ANOVA for comparing fibre lumen diameter between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	925.24	462.62	33.88**
Radial position within species	6	73.03	12.17	0.89^{ns}
Error	30	409.63	13.65	
Total	38			

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

XXIII. ANOVA for comparing fibre diameter between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	634.31	317.15	18.45**
Radial position within species	6	118.17	19.69	1.15^{ns}
Error	30	515.61	17.19	
Total	38			

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

XXIV. ANOVA for comparing ray percent between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	1014.81	507.40	17.70**
Radial position within Species	6	614.61	102.43	3.57**
Error	30	860.12	28.67	
Total	38			

*** significant at 0.01 level*

XXV. ANOVA for comparing vessel percent between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	8.51	4.26	2.72^{ns}
Radial position within species	6	10.54	1.76	1.12^{ns}
Error	30	46.93	1.56	
Total	38			

ns significant at 0.05 level

XXVI. ANOVA for comparing parenchyma percent between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	4068.74	2034.37	42.49**
Radial position within species	6	75.62	12.60	0.26^{ns}
Error	30	1436.40	47.88	
Total	38			

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

XXVII. ANOVA for comparing fibre percent between species and between radial positions

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	6786.26	3393.13	53.86**
Radial position within species	6	496.85	63.00	1.31^{ns}
Error	30	1890.08	82.81	
Total	38			

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

XXVIII. ANOVA for comparing heartwood percentage between species

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	3367.562	1683.781	21.494**
Within groups	10	783.367	78.337	
Total	12	4150.929		

*** significant at 0.01 level*

XXIX. ANOVA for comparing bark thickness between species

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	47.985	2	23.993	8.648**
Within groups	27.745	10	2.775	
Total	75.731	12		

*** significant at 0.01 level*

XXX. ANOVA for comparing log volume between species

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	0.02	2	0.010	10.840**
Within groups	0.01	10	0.001	
Total	0.03	12		

*** significant at 0.01 levels*

XXI. ANOVA for comparing sawn wood recovery between species

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	3.33	2	1.665	0.008^{ns}
Within groups	2199.66	10	219.966	
Total	2202.99	12		

ns-nonsignificant at 0.05 level

XXII. ANOVA for comparing CS at LP in compression perpendicular to the grain test at green condition

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	16093.413	2	8046.706	19.272**
Within groups	4175.349	10	417.535	
Total	20268.762	12		

** *significant at 0.01 level*

XXIII. ANOVA for comparing CS at LP in compression perpendicular to the grain test at air dry condition

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	10828.239	2	5414.119	10.374**
Within groups	5218.872	10	521.887	
Total	16047.110	12		

** *significant at 0.01 level*

XXIV. ANOVA for comparing Modulus of rupture (MOR) in static bending test at green condition

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	481571.663	240785.831	14.530**
Within groups	165719.863	10	16571.986	
Total	2185179591	12		

** *significant at 0.01 level*

XXV. ANOVA for comparing Modulus of rupture (MOR) in static bending test at air dry condition

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	564722.563	2	282361.282	14.647**
Within groups	192780.592	10	19278.059	
Total	757503.155	12		

** *significant at 0.01 level*

XXVI. ANOVA for comparing maximum load in static bending test at green condition

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	17299.845	2	8649.922	14.620**
Within groups	5916.558	10	591.656	
Total	23216.403	12		

*** significant at 0.01 level*

XXVII. ANOVA for comparing maximum load in static bending test at air dry condition

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	16978.448	2	8489.224	12.795**
Within groups	6634.919	10	663.492	
Total	23613.366	12		

*** significant at 0.01 level*

XXVIII. ANOVA for comparing Horizontal shear stress at maximum load (HS at ML) in static bending test at green condition

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	613.130	2	306.565	14.542**
Within groups	210.812	10	21.081	
Total	823.941	12		

*** significant at 0.01 level*

XXIX. ANOVA for comparing Horizontal shear stress at maximum load (HS at ML) in static bending test at air dry condition

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	664.652	2	332.326	13.594**
Within groups	244.472	10	24.447	
Total	909.124	12		

*** significant at 0.01 level*

XXX. ANOVA for comparing Horizontal shear stress at limit of proportionality (HS at LP) in static bending test at green condition

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	253.946	2	126.973	6.246*
Within groups	203.280	10	20.328	
Total	457.226	12		

** significant at 0.05 level*

XXXI. ANOVA for comparing Horizontal shear stress at limit of proportionality (HS at LP) at air dry condition in static bending test

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	272.740	2	136.370	10.463**
Within groups	130.342	10	13.034	
Total	403.082	12		

*** significant at 0.01 level*

XXXII. ANOVA for comparing fibre stress at limit of proportionality (FS at LP) in static bending test at green condition

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	199118.482	2	99559.241	6.223*
Within groups	159981.045	10	15998.104	
Total				

** significant at 0.05 level*

XXXIII. ANOVA for comparing fibre stress at limit of proportionality (FS at LP) in static bending test at air dry condition

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	227252.688	2	113626.344	10.893**
Within groups	104315.905	10	10431.590	
Total	331568.593	12		

*** significant at 0.01 level*

XXXIV. ANOVA for comparing the modulus of elasticity (MOE) at green condition in static bending test

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	2281900186.428	1140950093.214	12.426**
Within groups	10	918230133.241	91823013.324	
Total	12	3200130319.669		

** *significant at 0.01 level*

XXXV. ANOVA for comparing Modulus of elasticity (MOE) at air dry condition static bending test

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	1484922624.521	742461312.261	18.455**
Within groups	10	402315139.437	40231513.944	
Total	12	1887237763.959		

** *Significant at 0.01 level*

XXXVI. ANOVA for comparing compressive stress at limit of proportionality (CS at LP) in compressive strength parallel to the grain test at green condition

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	35841.274	17920.637	5.649*
Within groups	10	31723.470	3172.347	
Total	12	67564.743		

* *Significant at 0.05 level*

XXXVII. ANOVA for comparing compressive stress at limit of proportionality (CS at LP) in compressive strength parallel to the grain test at air dry condition

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	30622.380	15311.190	3.924^{ns}
Within groups	10	39014.552	3901.455	
Total	12	69636.932		

ns-nonsignificant 0.05 level

XXXVIII. ANOVA for comparing compressive stress at maximum load (CS at ML) in compressive strength parallel to the grain test at green condition

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	66594.478	33297.239	6.561*
Within groups	10	50746.457	5074.646	
Total	12	117340.935		

** Significant at 0.05 level*

XXXIX. ANOVA for comparing compressive stress at maximum load (CS at ML) in compressive strength parallel to the grain test at air dry condition

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	46870.960	23435.480	3.041^{ns}
Within groups	10	77058.413	7705.841	
Total	12	123929.373		

ns-nonsignificant 0.05 level

XXXX. ANOVA for comparing modulus of elasticity (MOE) in compressive strength parallel to the grain test at green condition

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	524099406.008	262049703.004	13.642**
Within groups	10	192096446.988	19209644.699	
Total	12	716195852.996		

*** Significant at 0.01 level*

XXXXI. ANOVA for comparing modulus of elasticity (MOE) in compressive strength parallel to the grain test at air dry condition

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	1141905688.11	570952844.054	49.742*
Within groups	10	114782277.65	11478227.765	
Total	12	1256687965.76		

** Significant at 0.05 level*

XXXXII. ANOVA for compressive stress at 2.5mm deflection condition in compressive strength perpendicular to the grain at green condition

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	62035.286	31017.643	26.418**
Within groups	10	11740.965	1174.097	
Total	12	73776.252		

*** Significant at 0.01 level*

XXXXIII. ANOVA for compressive stress at 2.5mm deflection in compressive strength perpendicular to the grain at air dry condition

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	43609.990	21804.995	15.862**
Within groups	10	13746.590	1374.659	
Total	12	57356.580		

*** Significant at 0.01 level*

XXXXIV. ANOVA for modulus of elasticity (MOE) in compressive strength perpendicular to the grain test at green condition

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	106040305.83	53020152.915	21.956**
Within groups	10	24147970.12	2414797.012	
Total	12	130188275.95		

*** Significant at 0.01 level*

XXXXV. ANOVA for modulus of elasticity (MOE) in compressive strength perpendicular to the grain test at air dry condition

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	90763868.39	45381934.197	18.580**
Within groups	10	24424682.63	2442468.263	
Total	12	115188551.02		

** *Significant at 0.01 level*

XXXXVI. ANOVA for compressive stress at limit of proportionality (CS at LP) in compressive strength perpendicular to the grain test at green condition

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	16093.413	8046.706	19.272**
Within groups	10	4175.349	417.535	
Total	12	20268.762		

** *Significant at 0.01 level*

XXXXVII. ANOVA for compressive stress at limit of proportionality in compressive strength perpendicular to the grain test at air dry condition

Source	Degrees of freedom	Sum of squares	Mean square	F-value
Between species	2	10828.239	5414.119	10.374**
Within groups	10	5218.872	521.887	
Total	12	16047.110		

** *Significant at 0.01 level*

WOOD QUALITY EVALUATION OF TREE SPECIES RAISED IN RESEARCH TRIALS OF THE KERALA FOREST DEPARTMENT AT VARIOUS LOCALITIES

By

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2010-17-107

ABSTRACT

Submitted in partial fulfillment of the requirement for the degree of

MASTER OF SCIENCE IN FORESTRY

Faculty of Agriculture

Kerala Agricultural University

DEPARTMENT OF WOOD SCIENCE
COLLEGE OF FORESTRY
KERALA AGRICULTURAL UNIVERSITY
VELLANIKKARA, THRISSUR,
KERALA, INDIA
2012

ABSTRACT

A study entitled "Wood quality evaluation of tree species raised in research trials of the Kerala Forest Department at various localities" was conducted in the College of Forestry, Kerala Agricultural University, Vellanikkara, Thrissur during the period 2010-2012. The objective of the study was to evaluate the wood quality of *Pterocarpus dalbergioides* Roxb., *Swietinia macrophylla* King. and *Pericopsis mooniana* (Thwaites) Thwaites, raised in research trials of the Kerala forest department at three localities, viz., Mananthavady research range at Wayanad, Olavakkode research range at Palakkad and Nilambur north research range at Nilambur districts, Kerala. Increment core samples and wooden blocks were collected at breast height from trees, selected at random for each species. These samples were subject to intensive investigations to explore the radial variation in anatomical properties as well as variation between species. The study revealed that most of the anatomical properties varied significantly within species and between species. Tree species were also felled to assess the strength characteristics as well as to study the various physical properties. Specific gravity was higher in *P. mooniana,* the other two species showing similar values. Heartwood – sapwood ratio showed significantly higher value in *S. macrophylla*, whereas the other two species were at par. Tangential shrinkage showed higher value compared to radial shrinkage in all the three species. Results revealed that *P. mooniana* exhibited better strength properties which was almost similar or even better than teak as reported by Sekhar (1988). *P. dalbergioides* showed lower values for strength properties when compared to natural grown *P. dalbergioides* (Limaye, 1933). Even though *P. mooniana* showed higher strength properties compared to the two species, overall results revealed that all the three species has good potential for being used as various solid wood purposes. Regression analysis revealed that *P. mooniana* and *P. dalbergioides* showed linear relationship between specific gravity and anatomical properties. The present results on wood quality can be used as a baseline data for future tree improvement aspects of these species with reference to wood quality and bring out their potential utility for future afforestation programmes and various end uses.