WOOD PROPERTY PROFILING OF COCONUT PALMS GROWN IN DIFFERENT AGRO-CLIMATIC ZONES OF THRISSUR DISTRICT, KERALA

by

ALEX. K. GEORGE

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THESIS

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DECLARATION

I hereby declare that this thesis entitled **"WOOD PROPERTY PROFILING OF COCONUT PALMS GROWN IN DIFFERENT AGRO-CLIMATIC ZONES OF THRISSUR DISTRICT, KERALA"** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

Vellanikkara
26.04.2017

Alex. K. George
(2014 – 17 – 115)

CERTIFICATE

Certified that this thesis entitled **"WOOD PROPERTY PROFILING OF COCONUT PALMS GROWN IN DIFFERENT AGRO-CLIMATIC ZONES OF THRISSUR DISTRICT, KERALA"** is a record of research work done independently by **Alex. K. George (2014-17-115)** under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to him.

Vellanikkara
26.04.2017

Dr. E. V. Anoop
(Major Advisor, Advisory Committee)
Professor and Head
Department of Wood Science
College of Forestry

CERTIFICATE

We, the undersigned members of the advisory committee of Alex. K. George (2014-17-115), a candidate for the degree of Master of Science in Forestry, agree that this thesis entitled **"WOOD PROPERTY PROFILING OF COCONUT PALMS GROWN IN DIFFERENT AGRO-CLIMATIC ZONES OF THRISSUR DISTRICT, KERALA"** may be submitted by Alex. K. George (2014-17-115), in partial fulfillment of the requirement for the degree.

Dr. E. V. Anoop,
(Chairman, Advisory Committee)
Professor and Head
Department of Wood Science
College of Forestry, Vellanikkara

Dr. K. Vidyasagaran
(Member, Advisory Committee)
Dean, Professor and Head
Department of Forest Management and Utilization
College of Forestry, Vellanikkara

Dr. A. V. Santhoshkumar
(Member, Advisory Committee)
Professor and Head
Department of Tree Physiology and Breeding
College of Forestry, Vellanikkara

Dr. C. M. Jijeesh
(Member, Advisory Committee)
Assistant Professor
Department of Silviculture and Agroforestry
College of Forestry, Vellanikkara

EXTERNAL EXAMINER

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Alex K. George

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INTRODUCTION

I. INTRODUCTION

Cocos nucifera L. (coconut palm), family Arecaceae (Renuka *et al.,* 1996) is the only species of the genus Cocos (Henderson, 2009). It is one of the world's most versatile and economically important palm (Moore, 1948; Subramaninan, 2003). The palm is also known as "Kalapavriksham" or "Tree of Heaven" (ENVIS, 2014) because of its multi utility nature. Coconut palm is being cultivated for more than 4000 years (Killmann and Fink, 1996) and is well known for its commercial, industrial and household uses in the tropic and subtropics, the history of which can be traced to an Egyptian monk, Cosmos Indicopleustes around 545 A.D to the work of an Italian explorer Lodovica di Varthema titled as Itinero of 1510 (Harries, 1992).

Coconut palms are grown in tropical and sub-tropical regions (Foale and Harries, 2011; Harries and Clements, 2013) where the availability of timber has declined over the years. Coupled with this, the demand for timber has increased because of the growing population and improved living standards. The advent of steel and other materials as a substitute for wood has not reduced the demand for wood. The consistent increase in plantations (FAO, 2015) of various species across the country for years couldn't bridge the gap between demand and supply. This gap in timber demand and supply cannot be reduced by imports alone as worldwide timber supply is becoming scarce. Sustainable and efficient utilisation of available wood sources and other lignocellulosic materials could possibly reduce this gap between demand and supply (Amartey *et al.*, 2006; Arancon, 1997; Wong *et al.*, 2005). In this scenario, the fibre resource from 12 m ha of coconut palm plantations (Fathi, 2014; APCC, 2014) if utilised judiciously could bridge the demand and supply gap.

Asia-pacific region encompasses 75-80 % of world's coconut palm plantations (APCC, 2014), where rapid economic development and population growth happens. India is one of the largest producer of coconut, accounting for 31 % of production and 17.6 % of the planted area (APCC, 2014). In India, coconut palms are grown mainly along the coastal regions. The bulk of the planted area, more than 90 % of coconut palm plantations are concentrated in the southern states of Kerala, Karnataka, Tamil Nadu and Andhra Pradesh.

Kerala, the land of 'kera' accounts for 33 % of India's total coconut palm cultivated area. Coconut palms are widely distributed in Kerala from home gardens to plantations, 98 % of the holdings sized less than two hectares. Coconut palm cultivation in Kerala extends to 8,08,647 ha (20.8 % of the total geographical area of Kerala) which is approximately 75 % (10,81,509 ha) of the total forest area of the state (GOK, 2015; FSI, 2015). Kozhikode district stands first in the cultivation of coconut palm with an area of 1,23,115 ha representing 15% of the cultivated area. Malappuram and Thrissur districts are in the second and third positions with an area of 13 % (1,05,481 ha) and 11 % (87,177 ha) respectively (GOK, 2015).

Large areas of coconut palm have senesced and consequently, copra yields have significantly reduced below economically viable levels of production. Coconut plantations across the globe have approximately 360 million non-productive palms (Fathi, 2014). In India about 20 % of the palms are senile. Hence the ineluctable rejuvenation and replanting will make available large quantities of coconut palm wood (Arancon, 2009; APCC, 2014). This utilisable palm wood can be substituted with conventional timber to meet our needs.

Coconut palm wood (non-wood lignocellulosic material) has been proven to be a good substitute to many conventional timber. Many scientists all around the world have considered coconut palm as an alternate source of wood to meet needs in the wood market (Yudodibroto, 1980; Arancon, 1997; Okai, 2004; Amartey, 2006;). Like conventional wood, the coconut stem is durable, sturdy and versatile and can often be used at considerably lower cost. The cost of coconut palm wood is only about half or a little more than half the price of conventional wood traditionally used for structural purposes (APCC, 2000).

Being a monocotyledon, the structure of palm trunk differs from conventional timbers. This is mainly evident in tissue structure and composition, density, moisture content, ash, silica and sugar/starch content. An understanding of these features is very much relevant in coconut palm wood processing, product design and product properties and performance.

The variability makes wood a versatile building material. There is tree to tree variability, variability within trees, variation from pith to bark and variation from the base to the top. These variations are influenced by factors like species, age and environment (Zobel and Buijtenen, 1989). Coconut palm wood properties also vary considerably. Understanding variations in properties of coconut palm wood is a need of the hour to develop standards for timber grading and for effective utilisation of the available variability.

Researchers all around the world have worked nearly on all aspect of coconut palm and have come out with new varieties and new processing techniques to make the palm more profitable for the survival of the coconut farmers. However, one of the less researched aspects is the utilisation of coconut palm wood. Even though there are real world examples for utilisation of coconut wood, the full potential of palm wood is not yet achieved as anatomical, physical and mechanical property variation within and between the palms are not fully comprehended and the information is inadequate for developing coconut palm wood processing techniques.

The present study is an attempt to quantify the variations due to age and locality on the wood properties of coconut palms grown in different agro-climatic zones of Thrissur district, Kerala. A sound understanding of palm wood properties and it's a foresaid variation are much relevant for palm wood processing, product design and performance, enabling efficient and effective utilisation of large volume of coconut palm wood available during felling of senile and diseased palms in the district. The information developed will also be useful in breeding programs to possibly develop 'nut-timber' varieties of coconut palms. The increased utilisation of coconut wood can reduce the dependency on forest or conventional plantation grown timber and can provide additional income to the coconut farmers. It will also to help eliminate the menace of felled senile palms being the breeding ground for the rhinoceros beetles (*Orystes rhinoceros)*.

The objectives of the study titled "Wood property profiling of coconut palms grown in different agro-climatic zones of Thrissur district, Kerala" are

1) To understand the anatomical, physical and mechanical properties of coconut palm wood

2) To analyse variation in these properties in coconut palms of different age group grown in different agro-climatic zones of Thrissur district.

REVIEW OF LITERATURE

II. REVIEW OF LITERATURE

Palm wood is competitive to commercial timber species. Several aspects of it have been discussed in the following sections, particularly coconut palm wood as a raw material source and its anatomical, physical and mechanical characteristics.

2.1. Coconut palm as wood

Palms are monocotyledon which means that the structure of the trunk is different from conventional timber. This is mainly evident in the tissue structure and composition, density, water content, ash, silica and sugar/starch content. Palms are resistant to fire, pathogens and are minimally susceptible to wind damage. The disability of palms to undergo dormant periods restricted their distribution to tropics and sub-tropics (Tomlinson, 2006). The absence of secondary growth causes palms to be columnar rather than tapering (Weiner and Liese, 1988).

Being monocotyledons coconut palm shows distinct differences in the wood structure compared to common wood species (Oduor and Githionim, 2006). The coconut palm has a smooth, slender stem that grows to a height of about 25 m with an average diameter of 300 mm. The densest part of the wood is found on the outer perimeter of the trunk, towards the centre wood gets relatively softer (Arancon, 2009). Trunk slender and slightly swollen at the base, usually erect but may be leaning or curved (Orwa *et al.*, 2009). Coconut palms have no vascular cambium. Hence, its trunk once formed does not increase in diameter with age (Odour and Githionim, 2006).

A coconut palm is divided into roots, trunk and crown but it does not have bark. Instead, the epidermis hardens to form a protective layer. The trunk consists of ground parenchymatous tissue and embedded vascular bundles. The composition of vascular bundles and parenchyma resulted in a typically reinforced material (like steel reinforced concrete) (Tomlinson, 1990; Fathi, 2014). One terminal growing point (apical meristem) is protected underneath a layer of leaves. Once the palm nearly reaches final thickness, it begins to grow in height. Growth can be very slow, lasting several years because the apical bud must reach a certain size before the trunk can develop (Cousins and Meylan, 1975; Jones 1995). In cross section, the stem has three distinct zones, dermal (most peripheral), sub-dermal (transitory zone) and the central or core. (Odour and Githionim, 2006).

The most remarkable feature of woody monocotyledons is that most of them achieve their stature without secondary growth. Their 'wood' is primary tissue and in developmental terms, it is not comparable to the wood of angiosperms and gymnosperms (Tomlinson and Zimmermann 1967).

Today coconut palm is an important economic crop in many regions of Southeast-Asia and the Pacific. Coconut stems have been used in all coconut producing areas. All parts of the palm can be utilised, because of this the palm is referred as 'green tree' (Khairul *et al.,* 2009). Coconut wood has been proven to be a good substitute for conventional wood. Like conventional wood, the coconut stem is durable, sturdy and versatile and it can often be used at a considerably lower cost (APCC, 2000). In lumber trade coconut palm wood is known as 'porcupine wood'. Seasoned coconut palm wood has a peculiar as well as attractive grain and a dark wine colour (Moore, 1948).

As the taper is very small of about 5 mm (FAO, 1985), the average sawn lumber recovery from a coconut palm is about 0.15 m^3 to 0.3 m^3 (Gnanaharan, 1987; Arancon, 1997). Root wilt disease does not affect sawn timber output from the diseased palms (Gnanaharan *et al.*, 1986).

The maximum diameter at the bottom of the coconut palm stem is around 25 cm - 30 cm (FAO, 1985; Killmann and Fink, 1996; Odour and Githionim, 2006; Arancon, 2009). The small diameter of coconut stem limits the size of sawn lumber, hence the optimum width and thickness of boards that are usually recovered are 25 mm and 50 mm (Arancon,1997). Average tree heights range between 15 m to 20 m but only the 2/3 (5 m to 8 m) of the stem can be used as construction material, the wood from the top and centre of the trunk being too light. The stems are converted into wood products in small-scale, often in very rough form, and used as a substitute for conventional timber in building and bridge construction, for tools, handicrafts, toys, furniture and others (Khairul *et al.*, 2009). In Maldives, coconut palm wood has been traditionally used for building fishing boats. Depending on the position in the trunk, the main potential end-uses for coconut palm wood are for construction, panelling, stairs, window and door jambs, flooring and power poles (Mead, 2001).

Experience has shown that almost the entire range of coconut palm wood can be used in appropriate functions in the construction of buildings, particularly houses. Structural load bearing components in the house should be made from dense timber grades. Trusses and internal members are made of medium density material and it has been possible to develop a wide range of advanced designs for the former (FAO, 1985; Arancon, 2009; Adkins and Foale, 2010; Jayabhanu, 2011). In addition to conventional methods of manufacture, nail plates and truss jigs facilitate the accurate prefabrication of trusses. Designs have been prepared to cover a range of uses from small thatched roofs, through several house types, to school room buildings. Floors and steps are made of hard material either as machined boards or parquet. The internal linings of the walls of houses may be made of soft wood, which is quite suitable for non-load bearing surfaces, although harder wood is used when a high finish is required. Because of size limitations, the use of coconut wood in larger building necessitates the adoption of laminated members. This technique has proved to be successful. Some very advanced beams have been made by combining laminated coconut palm wood sections with plywood webbing (Anoop *et al.*, 2011).

The performance of coconut palm wood in industrial uses construction and housing is closely related to its physical/mechanical properties and anatomical characteristics (Mitchell, 1964; Gurfinkel, 1973). For load bearing structures, high density or medium density coconut palm wood showed quite good properties, the usage of wooden elements (gluelam and cross laminated timber) caused no problems (Hasemann, 2012). Non-load bearing uses like the roof, wall and floor elements are possible with medium density coconut palm wood. All density classes of coconut palm wood are suitable for furniture and interior decoration. However, the coconut palm requires both a special sawmill procedure (based on three zones) to obtain good quality lumber that will perform well when used and it needs special tools for processing (Killmann and Wong, 1988). Due to the drawbacks of at least medium or low density, coconut palm wood has low natural durability. This is not a serious problem for dry interior use, but a major problem for exterior uses. Appropriate wood preservation is necessary (Fruhwald *et al.,* 1992). As the palm has no branches there are no branch remains (knots) in the wood. Consequently, no piece is weakened by the presence of natural defects (FAO, 1985). Marino (2010) also proposed the production of high value flooring, bench tops and furniture from the senile coconut palm.

Hopewell (2010) has proposed the usage of low density core portion of the coconut palm stem for ethanol distillation, compost and potting media, core plate for door manufacturing and suitability of high density portion for flooring. He found that coconut palm wood properties for bulk density (0.09 g vol^{-1}.), water retention efficiency (61 %), wettability (55 seconds), water holding capacity (44 %), and pH (6.2) are comparable with other products being used as potting medias.

Coconut fibre-cement boards (CFB) can be produced by mixing coconut wood chips with cement in the ratio 3:7 (Arancon, 2009). A study by Lertwattanaruk and Suntijitto (2015) estimated CFB's density (550-650 kg m^{-3}), bending strength (8.3 kg m^{-2}) and thermal conductivity (0.09 W m^{-1} K^{-1}).

Sulc (1983) recommended using coconut palm for transmission poles, in pole-type buildings like sawmill structures, wood drying open-side sheds, woodworking shops and agricultural auxiliary buildings, marine piles and general wharf structures, fencing (corner or gate posts) and round wood split into halves and quarters.

Sudo (1980) has found that only the most recently formed part of the over mature and mature sterns or young sterns seem suitable for pulping. Both unbleached and bleached coconut palm wood pulps showed moderated strength properties (Zerudo and Escolano, 1976). According to Killmann and Fink (1996), it is not feasible to make face veneer for plywood because coconut palm veneer sheets disintegrate during drying; it is technically feasible but uneconomical to manufacture pulp and paper and to manufacture chipboard and fibreboard due to the high percentage of fines and high consumption of glue.

Coconut palm saw dust treated with 1 % nitric acid can be used as cattle feed and the fodder qualities are comparable to normal silage (Gonzalez, 1979). Coconut palm wood has a reasonably high calorific value, country-type brick kiln operators prefer the wood due to its low cost and it is believed that a combination with cashew wood would enhance the reddish tint to the bricks due to the presence of resins (Gnanaharan, 1987). It can also be used for producing charcoal. The high-density portions of the trunk yield higher charcoal recovery and better quality compared to that of the low-density portions. Experience has also shown that good quality charcoal can be obtained from logging and sawmilling residues like coconut trunk slabs and timber off-cuts and from the butt part of the trunk. The upper portion of the trunk, consisting of low-density wood, gives charcoal of inferior quality (Gnanaharan *et al.*, 1988; Arancon, 2009). The palm wood charcoal is similar to charcoal obtained from *Leucaena leucocephala* and the charcoal can be used to make activated carbon (Arancon, 2009) which can be a reliable source of carbon for the manufacture of various products (Arancon, 1997).

2.1.1. Constraints in using coconut palm wood

A coconut palm wood user faces several problems while using the palm wood. Due to its very high density at its periphery, usually saw gets out of the saw line and the presence of fine substances similar to sand will rapidly blunt the blade (Odour and Githionim, 2006). Studies by Hopewell *et al.* (2010) has revealed that a range of minerals in addition to silica, the high density and changing angles of vascular bundles causes abrasiveness to tool edges. The presence of thick walled sclerenchyma fibres and a high loading of minerals makes sawing difficult and very hard on processing equipment and wood-working tools (Subramanian, 2003). It is difficult to nail and splits are common in high-density wood finishes.

Only limited sizes of sawn lumber are available because of the small diameter of the coconut trunk. The optimum width and thickness of boards that can be usually recovered are 25 mm and 50 mm. For structures requiring larger sizes of lumber, glued lamination of the wood has to be produced to the desired dimensions (FAO, 1985; Anoop *et al.*, 2011).

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Untreated freshly-cut lumber can be easily attacked by moulds and staining fungi, identified as *Penicillium* spp., *Rhizopus* spp., *Acremonium* spp., *Scopulariopsis* spp., *Aspergillus* spp., *Paecilomycess* spp. and *Fusarium* spp. (Hopewell *et al.*, 2010; Bahmani *et al.*, 2014), especially if the material is not properly stacked and is exposed to humid environments during the air-drying process. Further degradation during air-drying can also be caused by decay fungi and pinhole borers. Hence, prophylactic treatment is necessary, if coconut palm wood is used for the production of high-value products for export.

If coconut palm wood is not properly dried, checks and cracks develop on the surface in response to variations in relative humidity. Hence, drying of the wood should be done to bring its moisture content to an equilibrium in its location in service (Arancon, 2009).

2.1.2. Prospects to devoid constraints

The prospects of coconut palm wood as furniture are good especially now that many of the following problems related to use of coconut palm wood are already resolved. In order to avoid the blunting of sawing blade, it is necessary to use hard facing materials like tungsten carbide or stellite on the saw teeth (Odour and Githionim, 2006). It is difficult to nail the high-density wood and splitting at the edges is common. But this is remedied by pre-drilling before nailing. Furniture made of the high-density material is unusually heavy which is undesirable for domestic use. But this problem can now be minimised by using the medium and low-density material for the internal parts of furniture. The hard portion can be machined satisfactorily to obtain a smooth surface but machining the medium and soft materials may result in chipped grains. But extra sanding effort or using wood fillers resolves this problem. During staining, the soft portion absorbs more stain and tends to become darker than the other portions of the wood. But this can be controlled by applying a very thin coat of sanding sealer and lacquer thinner mixed at a ratio of 1:6 before staining. Glossy finishes applied over the softer portion tend to lose their lustre. But this can be corrected by applying more coating materials to the softer portion than to the harder portions. There is about 10-30 % change in

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finish consumption. The small size of the stem diameter limits the size of sawn timber. Normal logs provide sawn lumber with maximum width and thickness of 25 mm and 50 mm respectively. But to achieve lumber having wide surfaces, laminating the narrow pieces of wood together can solves this dilemma (Arancon, 2009; Anoop *et al.,* 2011).

Coconut palm trunk is treated as if it were true wood. However, the palm stem produces a significantly different material in physical, chemical and physiological characteristics and subsequently behaves in a different way. These differences are close enough to true wood for coconut palm wood to be processed with the same tools but far enough to diverge from known practices. New approaches to processing and product design was required in order for coconut palm wood to be processed efficiently and provide satisfactory performance in service (Hopewell, 2010). For this, a sound understanding of coconut wood properties is the prerequisite.

2.2. Characterization of coconut palm wood

Studies on coconut palm wood anatomical, physical, mechanical and chemical properties are reviewed here under

2.2.1. Anatomical features of coconut palm wood

Anatomical aspects of a large number of dicotyledons are well. On contrary, our understanding of the monocotyledonous anatomy and vascular system is very less because of their great complexity, which is largely beyond the reach of orthodox methods of investigation (Zimmermann and Tomlinson, 1972).

Palm trees actually do not produce wood; although, they do produce fibrous, wood-like stems. Even though cellular constituent of monocotyledons and dicotyledons are the same, they differ in their arrangement. Vascular development of coconut palm stem as described by Zimmermann and Tomlinson (1965, 1967, 1972, 1974), Tomlinson and Zimmermann (1967), Tomlinson (1970, 1990) and summarised in Tomlinson *et al.* (2011). The woody cylinder stems of angiosperm dicots and gymnosperms, such as teak, eucalyptus, sequoias, spruce and pines are produced from secondary growth that adds girth to the stem and consists primarily of secondary xylem made of cellulose and lignin. In fact, wood is often defined as secondary xylem (Raven *et al.*, 1999). Palm tree trunks result from only primary growth and reach their adult diameter near ground level. As described by Tomlinson (1961, 1964, 1990), Zimmermann and Tomlinson (1972), Parthasarathy and Klotz (1976a) and Tomlinson *et al.* (2011), the stem is made of a central cylinder with some concentric outer layers.

Palm stems can grow in girth by an increase in the number of parenchyma cells and the vascular bundles. This primary growth is due to a region of actively dividing meristematic cells called the primary thickening meristem that surrounds the meristem at the tip of the palm. In woody monocots, this meristematic region extends down the periphery of the stem where it is called the secondary thickening meristem. New vascular bundles and parenchyma tissue are added as the stem grows in diameter (Raven *et al.*, 1999). The most distinctive property of the palm stem is the ability of mature differentiated stem cells to retain their viability for centuries (Tomlinson, 2006). The palm stem xylem, phloem, and even parenchyma cells remain alive for the life of the palm (Magellan *et al.*, 2015; Broschat, 2013).

The main components of palm trunk are vascular bundles and parenchyma tissues. Both components are essential to the basic properties (Darwis *et al.*, 2013). The outermost layer is periderm, which is often replaced by other superficial protective tissues that become sclerified or suberized in the old stem. Under the periderm is a more or less developed cortex. Cousins and Meylan (1975) states that cortex is largely made up of unspecialized ground parenchyma containing numerous small longitudinal fibrovascular bundle strands. Subsequently, the central cylinder is abruptly demarcated from the cortex by the subcortical zone with many vascular bundles, sometimes crowded forming the peripheral sclerotic zone which provides mechanical support to the palm stem (Waterhouse and Quinn, 1978; Butterfield *et al.*, 1997; Gibson, 2012).

The number of vascular bundles is the closest relative parameter to the density and mechanical properties (Khozirah *et al.*,1991; Bakar *et al.*, 2013). Shirley (2002) and Erwinsyah (2008) have found that vascular bundles are not evenly spread but are concentrated on the outer and spread towards the centre of the trunk. Tomlinson (1961) and Weisberg and Linick (1983) claims that the number of vascular bundles per unit area of the stem is approximately the same at all heights. On contrary, Lim and Khoo (1986) traced that the number of vascular bundles increases from bottom to top but the density and mechanical properties are decreasing. This can be attributed to the young vascular bundles whose growth is still influenced by apical meristem. The density of vascular bundles at the trunk top is significantly lower compared to trunk base because of (a) the smaller diameter of vascular bundle resulting in (b) reduced area fraction of the fibre caps of the vascular bundle (vessel area remains almost constant) and (c) thinner fibre cell walls due to younger age of the cells and caused by less additional cell wall layers (secondary growth) (Arancon, 2009; Fathi, 2014).

The anatomical properties near "the bark" of the trunk are higher than the trunk core. The vascular bundle diameter does not vary significantly along the trunk diameter (Fathi, 2014). A study on the anatomy of coconut palm by Hopewell *et al.* (2010) revealed that the fibrovascular bundle architecture (grain angle) follows an interlocked, triple helix formation. This spiralling composition provides the coconut palm's excellent tolerance to high winds occurring during cyclonic and monsoonal seasons in exposed locations. But this spiralling bundles may cause twisting during the palm wood seasoning. The structure and distribution of the vascular bundles, as seen in the transverse section of the coconut palm trunk is related to their course in the stem before they exit at the nodes as leaf traces. The cells within the fibrovascular bundles are fibres with a honeycomb-like structure, while the ground tissue is made up of parenchyma with foam-like polyhedral cells (Butterfield *et al.*, 1997; Gibson, 2012). Further, some palms present a zone of transition with a decrease in the fibrovascular bundle density as well as a change in their structure toward the central zone of the stem (Waterhouse and Quinn, 1978). In other palms, the fibrovascular bundles are less variable and more evenly spaced throughout the stem (Gonzalez and Nguyen, 2016).

Corley and Tinker (2003) described the structure of vascular bundles. The orientation of vascular bundles within the trunk is not straight. With increasing

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height, the vascular bundles make their way from the peripheral region into the central region and then bend outwards to form several branches. These branches form a leaf trace which continues forming the leaf base. The leaf base is formed by many leaf traces. To connect the bundles some branches, bend towards the opposite direction or grow vertically which assures that all bundles are connected. This explains why the number of vascular bundles is higher in the peripheral zone and less but more even in the centre section. The bundles within the central part of the trunk form a spiral pattern (Corley and Tinker 2003). The vascular bundles have fibre caps of high density which give the wood stability and thus higher mechanical properties. The vascular bundles range from 1 mm to 3 mm in diameter depending on their location within the stem (Parthasarathy and Klotz, 1976b).

Each vascular bundle consists of a small vascular portion of one to four (usually two) large vessels surrounded by numerous fibres that thicken into a bundle cap on one end. Fibres provide structural support. Vessels conduct water. In wayward to the conducting elements of dicotyledons, palm vascular elements retain their conductive ability throughout the life span of the palm (Tomlinson, 2006). The xylem is always sheathed by parenchyma. The xylem usually contains two wide metaxylem vessels. The phloem or the food conducting tissue is a single strand and is found between the vessels and the bundle cap. In the centre of the stem vascular bundles are spaced far apart (Parthasarathy and Klotz, 1976a).

Towards the periphery of the stem, the vascular bundles become more numerous and crowded. The average count of vascular bundles in the centre is approximately around 10 vascular bundles per square centimetre and in the peripheral region the number drastically increases to 50 vascular bundles per square centimetre which does contribute to better strength properties in the peripheral region than the centre or pith (FAO, 1985; Fathi, 2014). According to Gibson (2012), the concentration of VBs, as well as the concentration of fibres within the bundles, is greater in the outer zone of the trunk than in the inner zone. Cell wall thickening is also more pronounced in the outer zone than in the inner zone of the trunk. This has a direct impact on the density and other mechanical properties of the wood (Kuo-Huang *et al.*, 2004; Erwinsyah, 2008).

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The different stem parts and different stems which have similar anatomical properties can have different densities because of a difference in vascular bundle area (Richolson and Swarup, 1977; Sudo, 1980). According to Kuo-Huang *et al.* (2004), the diameter of vascular bundles decreases not only from the base to the top but also from the core to the periphery. They also found that the density of vascular bundles decreases from the periphery to the core and from the top to the base.

Longitudinal cuts reveal that the vascular bundles form rod-like structures. The sap-conducting elements (vessels within the vascular bundles) occupy only about four to five percent of the total tissue volume compared with 30 % - 40 % for the vessels in most hardwoods and about 90 % for the tracheid in softwoods (FAO, 1985). Some species have fibrous bundles, which appear as small roundish bundles composed of sclerenchyma cells or fibres (Tidwell, 1998). In the central cylinder, fibrous bundles are found in some palms. Fibrous bundles are made of the same cells that make up vascular bundle cap. Xylem vessels of the palm resemble primary tissues of dicotyledons. Tyloses are rarely developed in coconut palm vessels and the rare occurrence is always a pathological phenomenon (Tomlinson, 1964).

The ground tissue consists of compact or lacunose parenchyma. The parenchyma tissue is not as resistant to decay as the wood of gymnosperms and dicot angiosperms. A ground parenchyma sustained growth, or a sustained parenchyma cell expansion occurs in the central cylinder of some palms. In many species, parenchyma cells become thick-walled and lignified with age. The ground parenchyma of low density has mainly a storage function and contains starch among other things. It is much softer with a variation of density across and along the stem. The anatomical features result in a rather non-homogenous distribution of physical properties both over cross-section and height (Parthasarathy and Kloot, 1976a; Tidwell, 1998; Fathi, 2014).

Sudo (1980) and Arancon (1997) found that with the sclerosis of fibres and parenchyma cells, density increases from the centre towards the outer most part and decreases from the base towards the top of the stem. Sudo (1980) identified anatomical properties such as the percentage of vascular bundle area per unit cross-sectional area, the diameter and the wall thickness of the vascular bundle fibres and the cell wall thickness of the ground tissue as the most influencing factors on the density and pulp quality of coconut palm. The area occupied by fibres in the vascular bundles decreases from the cortex to centre and with increasing stem height (Meylan, 1978).

The fibres usually have a well-developed secondary wall with a characteristically multi- layered appearance with the fibres in close association with silica containing cells known as 'Stegmata.' (Parthasarathy and Klotz, 1976b). Sudo (1980) found that fibre wall thickness within the vascular bundles decreases from bark to the centre, and from bottom to the top of the stem and thus influences the density. The microfibril angle ranges from 2^{o} - 20^{o} and the number of lamellae in the fibre wall appears to be closely related to total wall thickness (Meylan, 1978). The numbers of secondary wall layers in the fiber cells of the wide trunk were mostly lower than those in the fiber cells of the corresponding positions of the narrow trunk (Kuo-Huang *et al.*, 2004). Fibers have the ability to produce additional cell wall layers as they mature because they live throughout the life cycle of the palm (Tomlinson, 1990). The addition of new secondary wall layers on fiber cells contributes to the stiffness and density of the palm trunk (Bhat *et al.*, 1990).

In dicotyledons, ray elements conduct water radially. As monocotyledons lack ray elements, radial water conduction is facilitated by metaxylem of radially running leaf traces and their continuation in the axial bundles and through bridges (Zimmermann, 1986). The phloem and xylem continuity is maintained by anastomosis, by fusion with lower bundles (Weisberg, 1983).

2.2.2. Physical properties of coconut palm wood

The physical properties of coconut palm wood depend on density, moisture content and shrinkage. Differences in distribution of vascular bundles, the proportion of fibres to other cell types in vascular bundles and thickness of fibre and ground parenchyma cell walls are all responsible for variations in palm wood physical properties (Sudo, 1980) and even more the mechanical properties. The density of wood and the concentration of vascular bundles and elasto-mechanic properties per unit area are important parameters for visual or mechanical grading (Sulc, 1983).

2.2.2.1. Density

Density helps to determine the physical and mechanical properties and characterise different kinds of wood and woody materials for their intended use (Mitchell, 1964; Gurfinkel, 1973). Palm wood of the cortical zone is one of the hardest tissues known in the plant kingdom (Weisberg, 1983). Coconut palm wood shows a wide range in density within the trunk both crosswise and lengthwise. Coconut palm wood density can be high as 1000 kg m^{-3} which can be compared to conventional wood (Hopewell *et al.*, 2010). They reported the decrease in density from the periphery to the centre.

Jayabhanu (2011) observed the significant density variation in the coconut palm from the top to the bottom and from the central core to the periphery. Also, suggest only high density material (above 600 kg m^{-3}) is suitable for load bearing structures, coconut palm wood with a density below 400 kg m^{-3} should not be used as a load bearing structural component (Arancon, 2009). The palm wood density can vary so drastically in a single stem that it encompasses the entire density range as found across the timber industry from balsa to ironbark (Marino, 2010). Because of its inhomogeneity, Oduor and Githionim (2006) classified the palm wood as ranging from light and heavy due to its varying heterogeneity (density) over its cross section and along the stem height. Overall, the basic density ranges from 100 kg m^{-3} at the top core portion to 900 kg m^{-3} at the bottom dermal portion of old coconut palms (Arancon, 1997; 2009), which is 320 kg m^{-3} - 500 kg m^{-3} for *Pinus radiata* (Meylan, 1978).

Based on many years of practical experience with coconut palm wood in constructions, Sulc (1983) suggested the introduction of three density groups: high density (hard, above 600 kg m^{-3}), medium density (medium, 400-600 kg m^{-3}) and low density timber (soft, below 400 kg m^{-3}). Anoop *et al.* (2011) recommended Desch and Dinwoodie (1981) classification of coconut palm wood as hard, intermediate or soft based on density, high density (above 500 kg m^{-3}), medium density (between 500 kg m^{-3} and 350 kg m^{-3}), and low density (below 350 kg m^{-3}). Based on density, methods can be developed to determine the physical and mechanical properties (Fruhwald *et al.*, 1992).

Coconut palm wood between 15 m and 20 m height, even the outer zone of the stem lies in the medium density range while centre and top are already of low-density (Jensen and Killmann, 1981). The density at any particular height and cross-section increases with the age of the palm. Among the factors that influence density, number of vascular bundles per unit area (vascular bundle frequency) is the most important parameter. This parameter does also influence the mechanical properties (Darwis *et al.*, 2013). The density can vary within individual lengths of coconut palm wood depending on how widespread or congested the bundles (each bundle has its own density) at any point (Peters *et al.*, 2014).

Richolson and Swarup (1977) have observed that the density of swollen butt region was lower than the region above. Meylan (1978) states that the density of coconut palm wood is affected mostly by sclerenchyma fibres, the contribution of ground parenchyma to density is much greater than elsewhere in the plant community.

Hopewell *et al.* (2010) stated that there were no significant variations in key properties (density) between sites (high inland and low coastal) for similar age material from Fiji and Samoa. According to him, there is a wide range of within palm variation and the extent of this range is similar from site to site. The appearance of coconut palm wood is distinctive. The grain is strong and irregular so that the texture is variable. There is also a noticeable colour variation, sometimes related to density, the denser wood being darker (FAO, 1985).

Kloot (1952) noted that the ground parenchyma cells become thicker walled and darker in colour from the centre to the periphery of the trunk. Contrary to previous assumptions, Hopewell *et al.* (2010) stated that colour is not the best indicator of density and younger, paler coloured coconut palm wood occurring higher in the stem can still achieve suitable hardness for high-value flooring. There is no significant difference in density of coconut palm wood from outer zone specimens from basal and middle positions of the palm (Gnanaharan *et al.,* 1986). The density of the wood can be also influenced by the mineral content in the wood that is influenced by the edapho-climatic condition where the palm grows. (Peters *et al.*, 2014).

The most important feature that determines the quality of the wood is its natural durability and is related to density. The lower density wood which is around 15 % of the entire palm, cannot be used as they tend to collapse while drying apart from their week strength properties (FAO, 1985). The advantage of utilising a higher density wood is, they are a little resistant to decay fungi and insect attack (Jourez and Van Acker, 2012). The fungal resistance of coconut palm wood decreased from the outer to the inner sections and from the butt end to the top portion and also varied among location (Ballon, 1984). It has been also reported that the coconut palm wood having density more than 1000kg m^{-3} are better resistant to termites than that of lower density. However, untreated coconut palm wood cannot be considered as termite resistant (Hopewell *et al.*, 2010; Owoyemi *et al.*, 2013; Peters *et al.*, 2014). A highly negative relationship was obtained between density and dry salt retention, one of the factors that determines the treatability of coconut palm wood (Ganaharan and Dhamodaran, 1989).

The increase in density reflects the higher amount of wood substance which influences the strength of the material (Sekhar *et al.,* 1962). Gnanaharan and Dhamodaran (1989) interpreted density as an indicator of the age of the palm indirectly signify that the density increases with the age i.e., the basic density at any particular height increases with the age of the palm (Meylan, 1978; Arancon, 1997). Arancon (1997) has compared coconut palm wood to conventional wood and noticed that high density coconut palm wood (697 kg m^{-3}) has outperformed *Dipterocarpus grandifloras* (619 kg m^{-3}), *Pentacme concorta* (441 kg m^{-3}) and *Shorea polysperma* (466 kg m^{-3}) in terms of density.

The percentage of the various density groups per trunk depends on variety, site, age, the sweep of palm and the extent of fungus and insect damage. A distribution pattern of high density 40 % - 50 %, medium density 20 % - 30 % and low density 20 % - 30 % was observed by Killmann and Fink (1996) in an 80-year-old coconut palm.

2.2.2.2. Moisture content

Richolson and Swarup (1977) and Killmann (1983) stated that moisture content in coconut palm is wide-ranging; it rises rapidly with increased stem height and markedly so from the peripheral zone to the centre of the central cylinder. The high moisture content will make the wood susceptible to mould and stain fungi (Odour and Githionim, 2006). Low density means less vascular bundles and more parenchyma; this resulted higher moisture content. Coconut palm wood moisture migration is faster than true wood and the palm wood will rapidly re-absorb moisture from the environment (Hopewell *et al.*, 2010).

Kloot (1952) and Arancon (1997) found that the moisture content is negatively correlated with the basic density i.e. moisture content decreases with increasing basic density and vice versa. The amount of moisture in a coconut palm increases with increasing stem height and decreases from the core to the cortex. The moisture content ranges from 50 % at the bottom outer portion to 400 % at the top core portion of the stem. Killmann (1983) measured that the moisture content is closely related to the oven-dry density; hard timber, above 600 kg m^{-3}, has a low moisture content and soft timber a high percentage. It is therefore suggested not to kiln-dry coconut lumber in mixed batches but to dry it always in accordance with the three density groups.

Little knowledge is available on sorption behaviour (equilibrium moisture content,). Fruhwald *et al.* (1992) tested EMC at several relative humidities and found it is similar to common timber species. This is explained by a similar composition of chemical constitutes, holocelluloses and lignin. The moisture content does influence the usage of wood as it has an undesirable impact on the strength properties. As of the moisture content does increase the elastic property of wood (Modulus of elasticity) which can be inferred from the usage of green wood for building bridges (Kharif, 2009). It the same elastic nature of the coconut palm wood has made it possible for shuttering purpose too.

2.2.2.3. Shrinkage

The dimensional stability of the wood is determined by the shrinkage/swelling anisotropy and the fibre angle within in the trunk. Shrinkage and swelling can cause defects such as checks and split. Here in coconut palm wood, the mixture of the high density of fibre caps of above 1 g cm^{-3} and the parenchyma of 0.10 g cm^{-3} - 0.25 g cm^{-3} in coconut palm wood shows a very inhomogeneous and anisotropic behaviour although the wood does not exhibit different shrinkage levels in radial and tangential directions. This was also observed by Arancon (1997). There is little difference between tangential and radial shrinkages; on average, tangential shrinkage is slightly higher than radial shrinkage (Richolson and Swarup, 1977; Killmann, 1983; Gnanaharan, 1987). Shrinkage is generally related to oven-dry density, that is it increases from the centre to bark. It also increases slightly up to about 10 m stem height and then declines. Shrinkage is closely correlated with the number of vascular bundles per square unit (Killmann, 1983).

Evidence on shrinkage values of coconut palm wood is somewhat contradictory. Volumetric shrinkage (green to oven dry) of 10 % for wood from the outer portion and from 5 % - 7 % for intermediate and centre portions was reported by Richolson and Swarup (1977). Killmann (1983) observed a 10 % volumetric shrinkage at the periphery but up to 22 % for low-density wood from the core. The shrinkage in all three directions may not exceed 3 % when dried from green condition to equilibrium moisture condition (FAO, 1985). Fruhwald *et al.* (1992) suggested that this high level might be due not solely to shrinkage of the cell wall substance but partly to cell collapse caused by excessively severe drying conditions. There is general agreement on the small differences between radial and tangential shrinkage of coconut palm wood. Longitudinal shrinkage is very low (under 1 %). Low-density wood (less than 200 kg m^{-3}) shows a marked tendency towards cell collapse. The shrinkage and grain orientation have a direct impact on the wood defect that happens when drying, with coconut wood there is no such grain differentiation so the material will dry uniformly and without cross-sectional distortion (FAO, 1985). Gnanaharan *et al.* (1986) observed that there is no significant difference in volumetric shrinkage among different age groups and between the basal and middle positions of the coconut palm.

2.2.3. Mechanical properties of coconut palm wood

Trees achieve mechanical efficiency essentially due to their unique anatomy that enhances their mechanical properties (Wegst, 2011). Mechanical properties of conventional wood do not vary significantly, but the concentric lignification of fibres as the age increases bestow significant mechanical property variation to the palm wood (Rich, 1987; Tomlinson, 2006). Palms are usually considered as natural structures that mechanically perform better than hardwoods or softwoods (Tomlinson, 2006), partially because of a superior hierarchical structure that maximises the biomechanical resistance, while minimising the amount of material used (Buehler, 2010; Wegst, 2011; Gibson, 2012). The resistance of coconut palm to splitting on felling can be assigned to the fibres under high tension in the lower portion of the trunk (Hopewell *et al.*, 2010).

All mechanical properties which define the use as a timber are closely related to density and thus with the distribution of parenchymatous tissues and vascular bundles. As mechanical properties of wood indicate the ability of wood to resist various types of external forces, static or dynamic, which may act on it (Sekhar *et al.,* 1962; Panshin and De Zeeuw, 1970; Killmann and Lim, 1985). Mechanical properties are very much important in the case of constructional and structural purposes. The properties not only vary within tree but also within individuals, with reference to the nature of their fibre structure but also with the moisture content, temperature and defects of wood. Sometimes the properties vary with reference to the varying conditions of growth, methods of testing and methods applied. The composition and structure of cellular elements, along with a high relative density of the fibrovascular bundles, give rise to high mechanical properties per unit mass. This, in turn, results in mechanically efficient natural structures (Gibson, 2012). This high mechanical performance is specifically observed in senile coconut palms, with the tall palm stem (more than 25 m) being able to withstand extreme weather conditions without failure. The increase in density reflects the higher amount of wood substance which thus influences the strength of the material (Limaye, 1952; Sekhar *et al.*, 1962; Panshin and De Zeeuw, 1970; Killmann and Lim, 1985). This trend is also noted by Lim and Khoo (1986) in oil palm wood.

The mechanical properties of the outer part of the solid coconut palm lumber are 50 % higher than the inner part (Khairul *et al.*, 2009). Studies towards understanding the orthotropic mechanical properties of coconut palm wood are limited and mainly focused on estimating the modulus of elasticity (MOE) and bending modulus of rupture (MOR) in the longitudinal direction (Kuo-Huang *et al.*, 2004; Bahtiar *et al.*, 2010). Odour and Githionim (2006) have estimated MOR (16.34 N mm^{-2} - 109.21 N mm^{-2}) for the bending strength and compression strength (9.84 N mm^{-2} - 77.56 N mm^{-2}) for crushing strength of coconut palm wood and found that are in the range from very weak to very strong.

Sulc (1983) assessed the mechanical properties of 80-year-old coconut palm stems from Mindanao, Philippines and Killmann and Wong (1988) compared those to oil palm. The mechanical properties in both palm species differ up to ten times across the stem. They are closely related to density and thus with the distribution of parenchyma and sclerenchyma tissues (Gonzalez *et al.*, 2014). However, a distinct difference can be observed: all mechanical properties of coconut palm wood exceed those of oil palm wood (Fathi *et al.*, 2014). Mechanical properties at given positions in coconut palm stem measured from the bottom and are higher than those in oil palm. This is due to the higher percentage of denser tissues in coconut palms (60 %) compared with oil palm (30 %).

Kloot (1952) compared the average bending strength of full-size palm logs with that reported in the literature for other commercial timbers such as Red pine (green) 48.0 MPa, Lodgepole pine (air-dry) 44.1 MPa and Western red cedar (oven dry) 47.9 MPa. Bending strength of coconut palm wood was determined as 47.4 MPa. Tamolang (1976) investigated coconut palm trunks for power and telecommunication poles. He stated that bending strength value of coconut wood from the Philippines (38.7 MPa) is more or less equivalent to those of Shorea species (*S. almon, S. manggasinoro, S. squamata*) and also of *Agathis philippinesis*, all with a mean bending strength around 39.0 MPa and MOE of 6000 MPa.

Guzman (1989) investigated the mechanical properties such as bending strength, compression parallel to grain and shear strength of coconut palm wood from Mexico and compared with another species such *Quercus castanea* and *Enterolobium cyclocarpum.* He concluded that all properties tested including bending strength, compressive strength and shear strength decrease from the periphery to the centre. Density strongly influence all mechanical properties tested; higher density values were always associated to higher mechanical properties. Coconut palm wood was highly variable regarding their physical and mechanical properties. He stated that the average MOR values at various positions shown that those values indicated a gradual decrease in MOR along the trunk depth, the mean values of MOR at peripheral, central and inner zones were about 76 N mm^{-2}, 55 N mm^{-2} and 31 N mm^{-2}, respectively. All mechanical properties of Mexican coconut palm wood were higher compared to *Enterolobium cyclocarpum* but lower compared to *Quercus castanea.* The strength properties of high density coconut palm wood compare favourably with *Dipterocarpus grandiflorus, Pentacme concorta*, and *Shorea polysperma* which are commonly used as structural materials for building construction (Arancon, 1997); in contrast, the low-density palm wood cannot be compared with these wood species.

Fruhwald *et al.* (1992) investigated the mechanical properties such as bending strength, compression strength, shear strength and impact bending of Indonesian coconut wood. They concluded that strength properties of coconut palm wood are within the range of common traditional timbers, though generally about 20 % - 30 % lower when compared on the basis of densities. This drawback can be compensated by either larger cross-sectional dimensions (for structural members under static or dynamic load) or by selecting wood in a higher density range. Density and related strength properties were strongly correlated with tree age.

According to Gonzalez *et al.* (2014), the green MOE in the longitudinal direction was found to be 9 to 26 times greater than the ones in the radial and tangential directions and observed similar values in tangential and radial direction.

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The compressive characteristic green MOR were found to vary from 0.3 MPa - 40 MPa, 0 MPa - 17 MPa, and 0 MPa - 15 MPa, in the longitudinal, radial and tangential directions, respectively. The characteristic green MOR in the longitudinal direction was found to be 3 to 6 times greater than the ones in the radial and tangential directions. The MOE and the MOR were found to be linearly correlated in all directions. It can be inferred from the study that the MOE (Green) in the tangential and radial direction was on par. Such that the differentiation between radial and tangential direction seems meaningless.

Correlation studies conducted by Hopewell *et al.* (2010) noticed that density and hardness are strongly correlated with lower density values but the correlation is weaker at higher densities. Gonzalez *et al.* (2014) have found that a strong correlation exists between green MOE and basic density.

Fathi (2014) studied mechanical properties (MOR and MOE) of individual vascular bundles of coconut palm and found that vascular bundles near the bark of the trunk show higher MOE (344 MPa) and MOR (25144 MPa) than MOE (228 MPa) and MOR (17636 MPa) near the trunk core. She found that MOR and MOE values of the palm wood are lower than a single vascular bundle. She also compared coconut palm wood to date palm wood and oil palm wood and concluded that coconut palm wood has much better mechanical properties than the other two. She also observed that the distribution mechanical properties are very much related to the position in the trunk; it decreases along the trunk height from the bottom to the top and also along the trunk diameter from the outer zone to the inner zone. Bahtiat *et al.* (2010) reported that MOE and MOR were highest on the coconut palm stem base at the dermal portion, while the lowest, at core of the stem top.

Fruhwald *et al.* (1992) stated that in addition to the mechanical strength of coconut palm wood, also nail and screw holding is lower than that of conventional species of comparable density. A study carried out by Kothiyal and Kamala (1996) compared mechanical properties of teak and coconut palm and found that suitability indices of coconut palm wood are higher than teak except for shear.

The average modulus of rupture of coconut palm wood is comparable to *Dipterocarpus* sp and is higher than those of *Shorea polysperma*, *S. negrosensis* and *Pinus insularis* (Alston, 1977). Bahtiar *et al.* (2010) estimated Young's modulus (8118 MPa - 8596 MPa) and modulus of rupture (118 MPa - 224 MPa) of coconut palm wood and were found to be comparable to conventional timber used for construction purposes in the USA. Gnanaharan (1987) compared MOR and MOE of coconut palm wood to *Albizia odoretissima, Artocarpus heterophyllus, A. hirsutus, Terminalia paniculata* and *Xylia xylocarpa* and seen that the palm wood from butt log 5 m to 7 m long from mature and over mature palms, both non-diseased and wilt affected are comparable to the construction timbers available in Kerala. The wilt disease does not affect the strength properties of coconut palm wood. Age do not have any effect on the different strength properties of coconut palm wood except for MOE (Gnanaharan and Dhamodaran, 1989; Okai *et al.*, 2004).

The mechanical efficiency of a characteristic coconut palm wood structure was superior to a treelike structure of uniform density and fibres parallel to the stem's axial direction. This mechanical efficiency was identified as equivalent to that for engineering CFRP (Carbon Fibre Reinforced Polymer) laminates (Gonzalez and Nguyen, 2016).

Bending modulus of elasticity (MOE) increased from the core to the dermal of the central cylinder and then decreased from the base to the top. The greater elasticity on the outer part of the central cylinder than on the inner one will provide greater stiffness, and prevent the breakage of the trunk due to external forces such as wind (Rich, 1987; Kuo-Huang *et al.*, 2004). The hardness tests carried out on the palm wood from the peripheral zone of butt logs showed a higher value of 10950 N when compared to european oak (5550 N), teak (5550 N) and kwila (8900 N) and also showed a correlation to wood density (FAO, 1985).

Espiloy *et al.* (1990) studied variation in wood quality of green and yellow varieties of coconut palm and found that the yellow variety averaged higher values than the green variety in fibrovascular bundle frequency, fibre length, cell wall thickness, relative density, compressive and bending strength, hardness, shear, toughness, amount of hot water extractives, holocellulose and starch contents. On the other hand, the green variety had higher values than the yellow variety in vessel length, vessel diameter, moisture content, shrinkage, ash content, alcohol-benzene extractives, lignin, pentosane and silica contents.

2.2.4. Chemical properties of coconut palm wood

The main wood constituents of coconut palm wood are similar to common timber species, but it has higher ash content. The proximate chemical composition is as follows: inorganic pure ash (0.75 % (0.25 % - 2.4 %)), silica (0.07 % (0.01 % - 0.2 %)), holocellulose (66.7 %), lignin (25.1 %), pentosans (22.9 %), starch (4.3 % - 4.6 %); the pH 6.2 (Arancon, 1997). Outer zones of coconut palm wood have the highest holocellulose content. Although the holocellulose content seems to decrease from the outer to the inner zone, it was not significantly different between the middle and inner zone (Sahari *et al.*, 2012). Fathi *et al.* (2014)'s UV-micro-spectrophotometry measurements revealed quantitative differences in the lignification of the vascular bundles from the outer and inner stem section. Tensile strength increased with a decreasing degree of lignification.

Cellulose is the main source of the mechanical properties of wood (Janssen, 1995). The cellulose content of coconut palm wood, about 42 %, is similar to that of most wood species (Rydholm, 1965), comparable to that in softwoods (40 % - 52 %) and hardwoods (38 % - 56 %). Cellulose content consistently decreased from the outer to the inner zone. The cellulose content is in the range to make coconut palm wood suitable for the paper and pulp industry (Sahari *et al.*, 2012). Vascular bundles in the outer part of the trunk have a higher concentration of cellulose when compared to inner zone (Fathi, 2014). The outer zone has the highest lignin percentage. There is no significant difference between the middle and inner zone of coconut palm wood. The higher lignin content contributes greatly to the higher strength properties of the outer zone. The lignin content of 25 % places coconut palm wood at the end of the normal the range of 11 % - 27 % reported for non-woody biomass and closely resembles the range reported for softwoods (24 % - 37 %) and hardwoods (17 % - 30 %) (Fengel and

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Wegener, 1984; Dence, 1992). Minor constituents of coconut wood are resins and tannins. Ash is a term generally used to refer to inorganic substances such as silicates, sulphates, carbonates, or metal ions (Rydholm, 1965). Coconut wood has significantly higher ash content (0.25 % - 0.75 %) than common woods (aspen: 0.43 %, yellow polar: 0.45 % and white oak: 0.87 %) but it is generally lower compared to the bark of most wood species (white oak bark: 1.64 % and Douglas-fir bark: 1.82 %). Higher ash content in coconut palm wood can adversely affect pulp processing (Sahari *et al.*, 2012). The high silica (hydrated silicon dioxide) content of palm woods is well known to saw-millers and is, a major obstacle to the use of coconut palm wood.

Chemical analysis of coconut palm wood by Hopewell *et al.* (2010) has found that there is no significant difference in silica content when compared to other commercial timbers in Australia and he speculates that the high silica content is due to the location of many coconut palm plantations on siliceous sands. The palm wood's high silica content imparts the palm wood's elasticity (Arancon, 2009). Khairul *et al.* (2009) also commented that the presence of silica does contribute to the strength properties. Coconut palm wood is comparable to Philippine hardwood/softwood and bamboo as far as holocellulose, lignin and pentosan content are concerned (Arancon, 1997). Tannin from the bark may be suitable for the production of a tannin-formaldehyde adhesive. The trunk and trunk core tannin content is very less and their tannin to non-tannin ratio was estimated to be less than one (Manas and Tamolang, 1976).

MATERIALS AND METHODS

III. MATERIALS AND METHODS

3.1. Materials

The study was carried out to understand the anatomical, physical and mechanical properties of coconut palm wood from different age groups grown in different agro-climatic zones of Thrissur district, Kerala. The study was conducted in the department of Wood Science, College of Forestry, Kerala Agricultural University, Vellanikkara.

3.1.1. Species studied

Cocos nucifera L., the coconut palm is also called porcupine wood because of its reddish-brown fibres embedded in a lighter tan or light brown coloured parenchyma. Coconut palm wood is medium to fine textured with, highly variable weight, strength and hardness properties. Towards the outer wall of the trunk, the density of the wood is the greatest with good dimensional stability and gradually becomes lighter, softer and weaker towards the core.

3.1.2. Location

The present study was carried out in Thrissur district (between N 10° 11' 8.16" and N 10° 41' 2.76" latitude; E 75° 58' 2.64" and E 76° 53' 29.04" longitude) of central Kerala, India. The district spans an area of 3,03,200 ha with coconut palm cultivation extending to 87,177 ha (28.75 %) (GOK, 2015).

3.1.2.1. Agro-climatic zones

Four parameters (altitude, rainfall pattern, soil type and topography) together creates a distinct agronomic environment which leads to distinct cropping patterns. Using a matrix built upon these parameters at its different levels, Kerala has been delineated into 13 agro-climatic zones with block panchayat as the unit of delineation. The study site, Thrissur district encompasses three agro-climatic zones namely Coastal sandy, Central midlands and Malayoram (KAU, 2011).

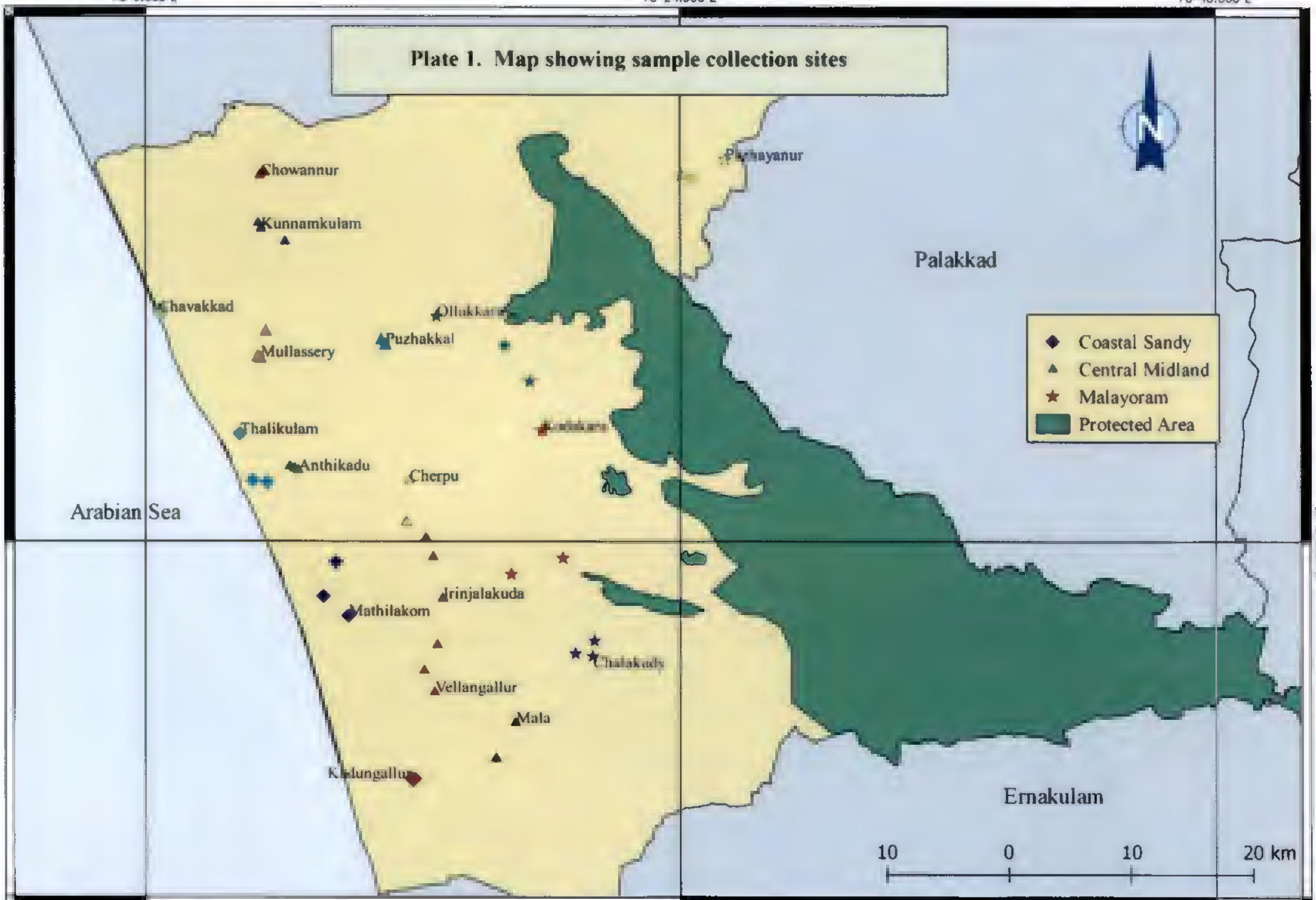

Plate 1. Map showing sample collection sites

Table 1. Details of sampled coconut palms from three agro-climatic zones of Thrissur district, Kerala.

Agro-climatic zones	Block	Age	DBH (cm)	Height (m)	Latitude N	Longitude E
Malayoram	Chalakudy	15	28.00	7.50	10.31352	76.33426
		35	24.00	13.00	10.31559	76.32146
		55	23.00	15.00	10.32521	76.33563
	Kodakara	15	26.00	8.00	10.48282	76.29637
		35	22.00	14.00	10.38729	76.31216
		55	21.00	16.00	10.37530	76.27371
	Ollukkara	15	27.50	8.50	10.56838	76.21776
		35	23.00	15.00	10.54641	76.26843
		55	24.00	17.00	10.51962	76.28750
	Pazhayanur	15	26.00	10.00	10.68576	76.43369
		35	23.00	14.00	10.67429	76.40073
		55	19.00	16.00	10.67125	76.40897
Central midland	Mala	15	27.07	11.00	10.26401	76.27696
		35	24.00	15.00	10.23738	76.26246
		55	25.00	18.00	10.23708	76.26271
	Vellangallur	15	22.00	10.00	10.28690	76.21626
		35	21.00	14.00	10.32211	76.21833
		55	26.00	16.00	10.30304	76.20847
	Irinjalakuda	15	24.00	10.50	10.35716	76.22242
		35	22.00	15.50	10.38823	76.21521
		55	26.00	17.00	10.40243	76.20970
	Cherpu	15	24.00	10.50	10.44554	76.19725
		35	24.00	14.00	10.41484	76.19467
		55	26.00	18.00	10.41410	76.19557
	Anthikadu	15	21.00	9.00	10.45336	76.11434
		35	22.00	14.70	10.45475	76.11155
		55	19.00	17.50	10.45625	76.10829
	Puzhakkal	15	23.00	11.50	10.54799	76.17932
		35	22.00	14.50	10.54767	76.17923
		55	22.00	18.00	10.55153	76.17614
	Mullassery	15	24.00	11.00	10.53823	76.08640
		35	24.00	15.00	10.53916	76.08425
		55	20.00	19.00	10.55840	76.09035
	Kunnam-kulam	15	27.00	8.00	10.63430	76.08689
		35	20.00	14.00	10.62457	76.10478
		55	22.00	16.00	10.63843	76.08483

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Cont.

	Chowannur	15	24.00	11.00	10.67427	76.08624
		35	23.00	14.00	10.67424	76.08599
		55	23.00	17.00	10.67635	76.08951
Coastal sandy	Kodungallur	15	27.00	10.00	10.22240	76.19885
		35	24.00	15.00	10.22215	76.20153
		55	23.00	18.00	10.22076	76.20013
	Thalikulam	15	26.00	11.00	10.48048	76.07099
		35	19.00	15.00	10.44436	76.09119
		55	22.00	19.00	10.44586	76.08068
	Mathilakom	15	26.00	12.00	10.34395	76.15160
		35	24.00	14.00	10.38445	76.14205
		55	25.00	20.00	10.35872	76.13300
	Chavakkad	15	26.00	11.00	10.57203	76.01020
		35	24.00	14.00	10.57350	76.01286
		55	22.00	18.00	10.56988	76.01110

3.1.2.1.1. Coastal sandy

Coastal sandy zone includes Kodungallur, Thalikkulam, Mathilakom and Chavakkad block panchayats. The zone has the altitude Type I i.e., up to 500 m above mean sea level (low altitude-humid tropics); rainfall (Pattern I) where both the south west and north east monsoon are active and moderately distributed, south-west monsoon with June maximum (south of 11° N latitude); topography (Model I) of extensive valleys with level but raised garden lands and sandy loam soil.

3.1.2.1.2. Central midlands

Mala, Vellangallur, Irinjalakuda, Cherpu, Anthikad, Puzhakkal, Mullassery, Kunnamkulam and Chowannur block panchayats were delineated to Central midlands. The zone has the altitude (Type I) up to 500m above mean sea level (low altitude-humid tropics); rainfall pattern I i.e., both the south west and north east monsoon are active and moderately distributed, south-west monsoon with June maximum (south of 11° N latitude); topography (Model IIa) where valleys are less extensive, hills with moderate gradients, slopes having mild gradients and laterite soil with well-defined B-horizon.

3.1.2.1.3. Malayoram

Malayoram includes Chalakudy, Kodakara, Ollukkara and Pazhayannur block panchayats. The zone has the altitude type I i.e., up to 500 m above mean sea level (low altitude-humid tropics); rainfall pattern I i.e., both the south west and north east monsoon are active and moderately distributed, south-west monsoon with June maximum (south of 11° N latitude); topography model III i.e., narrow valleys, hills with steep gradients, steep slopes and laterite soil without B-horizon.

3.2. Methods

The methods adopted to carry out the study has been discussed below.

3.2.1. Selection of samples

Coconut palms were selected from the three agro-climatic zones of Thrissur district following stratified random sampling technique. The experimental materials

Plate 2. Collection and preparation of samples

Felling of coconut palm

Demarcation of dermal, sub dermal core wood in felled palms

Sawing of felled palms

Stacking of sawned samples

were collected from 17 block panchayats (4 Costal sandy + 9 Central midlands + 4 Malayoram) from the three agro-climatic zones, which also include palms from age groups 55-65 years (over mature palms), 35-45 years (mature palms) and 15-25 years (young palms) (Gnanaharan and Dhamodaran, 1989).

Billets of 1 m length were collected from the butt end of 51 palms (3 palms from each block panchayat) felled conventionally or using a power saw. Coconut palm was divided into dermal (outer), subdermal (middle) and core (inner) zones radially (Arancon, 2009). The face ends of billets were painted with yellow (dermal) and blue (sub dermal) colour to distinguish the different zones of coconut palm wood. The billets were transported to the sawmill and were converted to sticks of 5 cm x 5 cm cross section for further analysis.

3.2.2. Core wood dermal wood ratio

In order to determine core wood dermal wood ratio, the palm trunks were divided into three equal parts along their radius. Coconut palm wood with density above 400 kg m^{-3} were considered as dermal wood and below 400 kg m^{-3} as core wood. Then the area of core wood and dermal wood was calculated and core wood to dermal wood ratio was estimated.

3.2.3. Physical Properties

Small clear wood specimens of 2 cm x 2 cm x 2.5 cm dimension were made out according to IS: 1708 (ISI, 1986) for estimating coconut palm wood's basic density, moisture content and shrinkage.

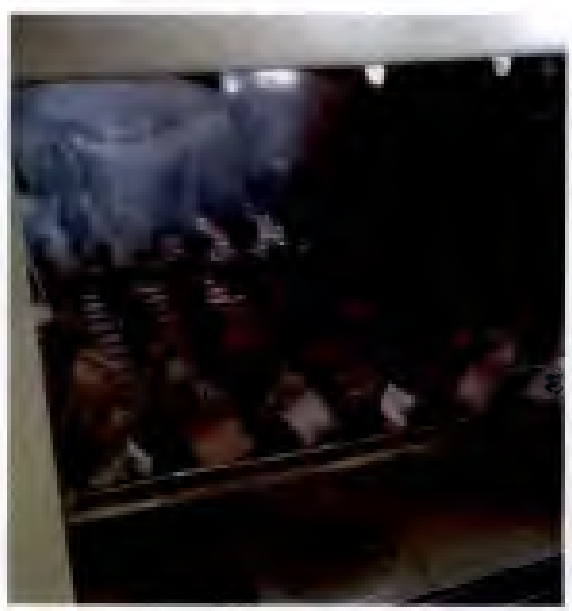
3.2.3.1. Basic Density

Green volume of the sample was estimated using the immersion method. The samples were oven dried at $103^0C \pm 2^0C$ until the weight became constant for the determination of oven dry weight using a precision electronic balance (Shimadzu AUY 220) and were weighed correct to 0.001g.

Plate 3. Profiling of physical properties in coconut palm wood

Sample preparation for physical properties estimation

Fresh weight measurement



Oven drying of samples

Basic density (standard specific gravity) for coconut palm wood specimens from three radial positions of each palm was determined using the following formula,

$$\text{Basic density}(\text{kg m}^{-3}) = \frac{\text{Oven dry weight}}{\text{Green volume}}$$

$$\text{Oven dry density}(\text{kg m}^{-3}) = \frac{\text{Oven dry weight}}{\text{Oven dry volume}}$$

3.2.3.2. Moisture Content

In order to determine moisture content, the samples were weighed with an accuracy of 0.001 in a weighing balance (Shimadzu AUY 220) and then dried in a hot air oven at a temperature of $103^0C \pm 2^0C$ till a constant weight. The final weight has been taken as oven dry weight. The moisture content of each specimen was calculated using the formula,

$$\text{Moisture content (\%)} = \frac{\text{Green weight} - \text{Oven dry weight}}{\text{Oven dry weight}} \times 100$$

3.2.3.3. Volumetric Shrinkage

To estimate volumetric shrinkage, the specimen was initially weighed in the green condition with a precision of 0.001 g and the volume was determined by immersion method with a precision 0.01 cc. A suitable vessel, half filled with water, was kept on the pan of a weighing balance and weighed correct to 0.001 g. The specimen was then completely dipped in water by means of a needle and weighed again. Care was taken such that no air bubble stick to the specimen and that the specimen was not touching the side of the vessel. The difference between the two readings is the green volume of the specimen. The specimen was then kept in a hot air oven at $103^0C \pm 2^0C$ until constant weight is attained. After oven-drying, the specimen was again weighed and oven dried volume was determined by immersion as before. The percentage volumetric shrinkage was given by the formula,

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$$\text{Volumetric shrinkage (\%)} = \frac{\text{Green volume} - \text{Oven dry volume}}{\text{Green volume}} \times 100$$

3.2.3.4. Dimensional shrinkage

Dimensional shrinkage includes longitudinal shrinkage, tangential shrinkage and radial shrinkage. As coconut palm wood is not known to have any significant variation in the radial and tangential direction (Killmann, 1983) shrinkage was not estimated separately for tangential and radial planes.

To estimate dimensional shrinkage, the length of the specimen was measured correct to 0.01cm by means of a digital vernier caliper. Centre and corners of specimen were marked to make subsequent measurements. The specimens were dried in an oven at $103^0C \pm 2^0C$ until a constant weight is attained. The specimens were then measured finally. The percentage dimensional shrinkage was given by the formula,

$$\text{Dimensional shrinkage (\%)} = \frac{\text{Initial length} - \text{Oven dry length}}{\text{Initial length}} \times 100$$

3.2.4. Anatomical properties

The anatomical features that were assessed include fibre morphology, vascular bundle sheath thickness, vascular bundle diameter, vascular bundle frequency, and vessel diameter.

3.2.4.1. Microtomy

Wood specimens of size less than 1 cm^3, made out from the samples were used for anatomical studies. The specimens were then softened by keeping in a water bath (Rotex water bath) at 80^0C for 15-30 minutes and hard samples were softened by keeping in a solution of alcohol and glycerol (ratio 3:1) in a desiccator attached to a vacuum pump. Thin microscopic sections (T.S) of 10 µm - 15 µm thickness were prepared using a sliding microtome (Leica SM 2000 R).

3.2.4.2. Staining procedure

Permanent slides of micro sections were stained using the procedure outlined by Johansen (1940). For this, sections were stained using safranin and later washed through a series of alcohol solutions at different concentrations (70 %, 90 % and 95 %) to ensure complete dehydration. They were subsequently dipped in acetone followed by xylene and finally mounted using DPX to prepare the permanent slides (size 75 mm x 25 mm x 1 mm) and covered using cover slips.

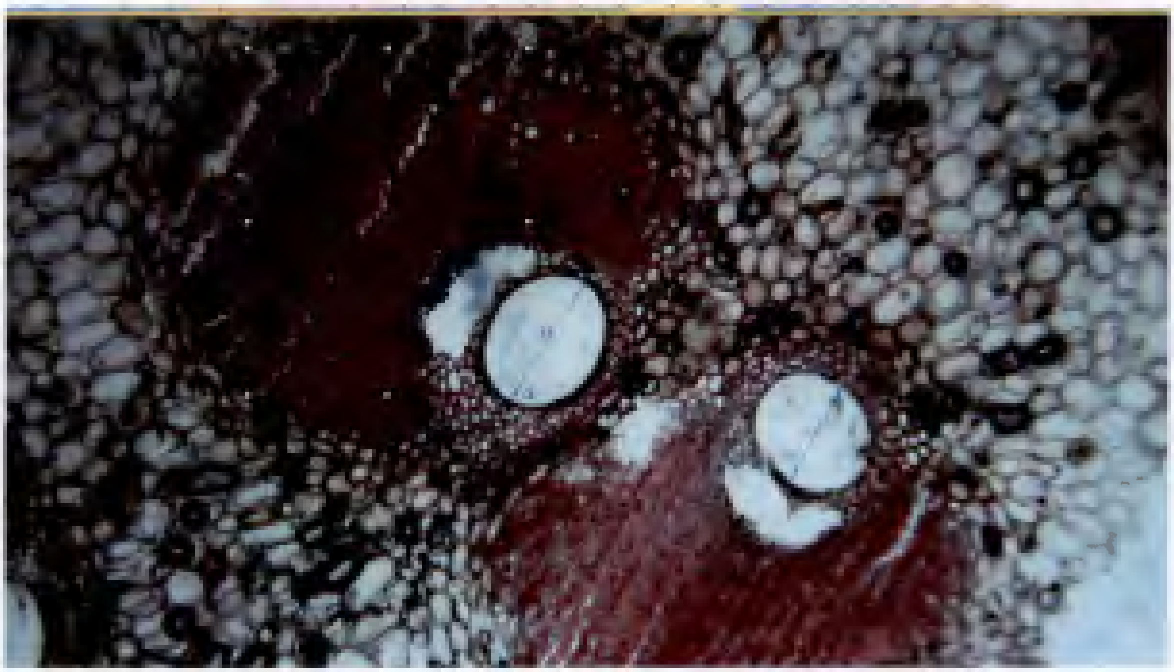
3.2.4.3. Maceration

Maceration of the wood samples was done by Jeffrey's method (Sass, 1971). For maceration, freshly prepared Jeffrey's solution (10 %) was used which was prepared by mixing of 10 g potassium dichromate and 14 ml nitric acid and volume was made to 100 ml. Radial chips of wood shavings were taken from the 1 cm^{-3} wood blocks separately from the three radial positions viz., dermal, sub dermal and core. These chips were boiled in the maceration chemical for 15 to 20 minutes so that the individual fibres get separated. Subsequently, these test tubes were kept undisturbed for 5 to 10 minutes so that the fibres settled down. The solution was discarded and the resultant material was thoroughly washed with distilled water until traces of acid were removed. The samples were stained using safranin and mounted temporarily using glycerol.

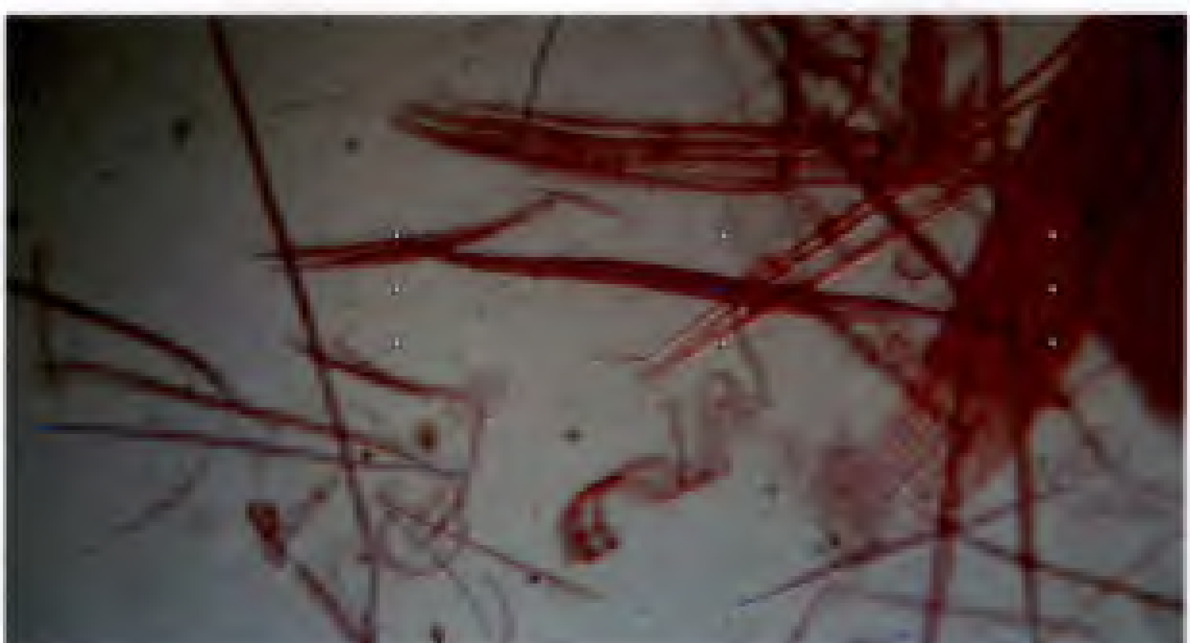
3.2.4.4. Image Analysis

Microscopic examination and quantification of sections were undertaken using an Image Analyzer (Labomed-Digi 2). The image analyser provides quick and accurate data replacing the more laborious traditional methods. The digital camera provides digitised images which are analysed by the software (Labomed DigiPro-2). The software provides several classes of measurements like length, diameter, area and count.

Plate 4. Profiling of anatomical properties in coconut palm wood



Transverse section (10x) taken using sliding microtome



Coconut palm fibre (10x) obtained by maceration

3.2.4.5. Observations

From the macerated fibres, observations like fibre length, fibre diameter, fibre wall thickness, and fibre lumen diameter and from microscopic sections vascular bundle diameter, bundle sheath thickness, vascular bundle percentage and vessel diameter were measured using the Image Analyzer. Each measurement was repeated five times for all the above characters at different radial positions of the palm wood and is expressed in micrometres (μm).

3.2.4.6. Vascular bundle frequency

The number of vascular bundles per unit area was estimated by counting the vascular bundles with the help of a 1 cm^2 grid and a hand lens of magnification 10x (Killmann, 1983). Before counting the vascular bundles the cross section of each specimen was sanded for better visibility.

3.2.5. Mechanical Properties

Assessment of mechanical properties was carried out in the Central Wood Testing Laboratory under the Rubber Board of India, Kottayam. Coconut palm wood with density above 650 kg m^{-3} (26 palms) were selected and were used for mechanical wood property testing.

3.2.5.1. Testing Instrument

All the mechanical properties except tensile strength parallel to grain were tested using an automatic Universal Testing Machine (UTM-Shimadzu 100 KgN) which is a computerised and sophisticated version of the manual UTM. The testing units consist of a jig where the samples are loaded for test and a head, whose upward or downward movement applies stress to the sample. The calibration of the instrument is controlled by a control keypad. This set up is associated with a computer installed with the software 'Winsoft", which sense the deflection and stress, and plots the load by deflection curve on the monitor simultaneously with the test. Before the start of a test, the instrument is calibrated for the type of test, rate of loading and dimensions of the samples as per IS 1708: 1986 (ISI, 1986).

Plate 5. Universal testing machine at Central wood testing laboratory, Kottayam

Universal testing machine (Shimadzu 100 KN)

Computer linked to UTM machine

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On completion of the test, the stress by strain graph can be directly read from the monitor and various parameters corresponding to the test can be recorded.

3.2.5.2. Preparations of test samples

Scantlings were air dried. Then the scantlings were converted to standard small clear specimens for different tests as per IS 1708: 1986 specified by ISI (1986). The samples were transferred to a conditioning chamber to condition all the samples to a uniform moisture percent of 12 ± 2 percent.

3.2.5.3. Testing of samples

The following tests for wood mechanical properties were conducted as per IS 1708: 1986.

3.2.5.3.1. Static bending test

Samples of size 2 cm x 2 cm cross section and 30 cm length were tested as per IS 1708 (part 5): 1986 (ISI, 1986). Before loading the sample for testing, the width and thickness were accurately measured. The samples were loaded such that the stress was perpendicular to the grain. The machine was calibrated to set the deflection and load at zero and the rate of loading was set at 1 mm per minute. Load by deflection curve was read from the monitor. The parameters viz., modulus of elasticity (MOE), modulus of rupture (MOR), maximum load, fibre stress at the limit of proportionality (FS at LP) and horizontal shear at the limit of proportionality (HS at ML) were estimated from further analysis. The software calculates MOE over a range of deflection at the 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 estimated.

(a) Fiber stress at limit of proportionality (FS at LP) ($kg\ cm^{-2}$) = $3PI/2BH^2$

(b) Modulus of rupture (MOR) ($kg\ cm^{-2}$) = $3P'I/2BH^2$

(c) Modulus of elasticity (MOE) ($kg\ cm^{-2}$) = $PI^3/4\Delta BH^3$

(d) Horizontal shear at limit of proportionality (HS at LP) ($kg\ cm^{-2}$) = $3P/4BH$

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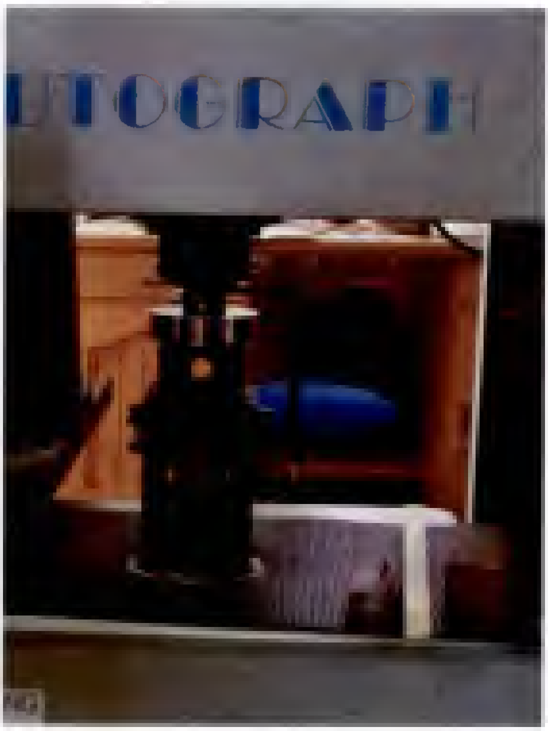
Plate 6. Profiling of mechanical properties in coconut palm wood

Static bending test



Shear strength

Tensile strength parallel to grain

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(e) Horizontal shear stress at maximum load (HS at ML) (kg cm^{-2}) = 3P'/4BH

Where,

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

I = Span of the test specimen in cm

B = Breadth of test specimen in cm

H = Depth of the test specimen in cm

P' = Maximum load in kg

Δ = Deflection in cm at the limit of proportionality

3.2.5.3.2. Test for compression strength parallel to grain

Samples of size 2 cm x 2 cm x 8 cm were tested as per IS 1708 (part 8): 1986 (ISI, 1986). Before the test, the width, thickness and length of the samples were recorded. The rate of loading was calibrated to 0.6 mm per minute and the load and deflection was set to zero. The sample was loaded with its longitudinal axis along the direction of movement of the head. Load- deflection curve is analysed through the reanalysis mode. A tangent is drawn in such a way that maximum number of points are in the straight line. Based on the limit of proportionality and maximum load, the compressive stress at limit proportionality, compressive stress at maximum load and modulus of elasticity were calculated using the formula

(a) Compressive stress at limit of proportionality (CS at LP) (kg cm^{-2}) = P/A

(b) Compressive stress at maximum load (CS at ML) (kg cm^{-2}) = P'/A

(c) Modulus of elasticity in compression parallel to grain (kg cm^{-2}) = LP/ΔA

where,

P = Load at limit of proportionality 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

3.2.5.3.3. Test for compression strength perpendicular to grain

Samples of size 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 vertical plane faces the stress. The linear dimensions of the sample were recorded before the test. The rate of loading was calibrated to 0.6 mm per minute and the deflection and load were set to zero. Various parameters were read from the monitor and graph adjusted to reanalyse the MOE. The following parameters were calculated using the formula,

(a) Compressive stress at limit of proportionality (kg cm^{-2}) = P/A

(b) Crushing strength at compression of 2.5 mm (kg cm^{-2}) = P'/A

(c) Modulus of elasticity in compression parallel to grain (kg cm^{-2})

$$= P/A \times H/\Delta$$

where,

P = Load at the limit of proportionately in kg

A = Area of cross-section normal to the direction of load or area of a metal plate used 3 cm x 2 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

3.2.5.3.4. Hardness test

Samples of size 5 cm x 5 cm x 15 cm were tested as per IS 1708 (part 10): 1986 (ISI, 1986). Load (KN) required to penetrate into the specimen by a steel bar with a hemispherical end or a steel ball of 1.128 cm diameter to a depth of 0.564 cm was recorded. Measurements were made at the centre of the planes and end faces and no splitting or chipping occurred. The rate of loading was kept constant at 6mm per minute.

3.2.5.3.5. Shear test

Samples of size 5 cm x 5 cm cross section and 6.25 cm length were tested as per IS 1708 (Part 11): 1986 (ISI, 1986). The specimens were notched at one end to produce shear failure in an area of 5 cm × 5 cm in the vertical plane. The samples were loaded such that the head of the machine rests exactly in the notch. The rate of loading was calibrated to 0.4 mm per minute and the load and deflection were set to zero. Various parameters were analysed by the following formula,

(a) Maximum shear stress (MSS) (kg cm^{-2}) = P/A

Where

P = Maximum load in kg

A = Cross section area of specimen in cm^2

Reanalysis was not done, as the parameters studied were independent of deflection at the limit of proportionality.

3.2.5.3.6. Tensile strength perpendicular to grain

Samples of 5 cm x 2 cm area with notches were made to produce a failure on the samples. The specimen was placed on the grip provided to hold the specimen. The load has been applied continuously throughout the test so that the movable head moves at a constant rate of 2.5 mm per minute until the maximum load is reached. The maximum load required for failure perpendicular to grain was also recorded.

(a) Tensile stress at maximum load (TS at ML) (kg cm^{-2}) = P'/A

where

P' = Maximum load in kg

A = Cross sectional area of specimen in cm^2

3.2.5.3.7. Tensile strength parallel to grain

The test has been carried out using Universal Testing Machine (Kalpak, K-test series, 15 KN). Samples of 5 cm and 1.5 cm cross section and 32.5 cm in length were tested as per IS 1708 (part 12): 1986 (ISI, 1986). The machine was calibrated to set the deflection and load at zero and the rate of loading was set at 1 mm per minute. Based on the limit of proportionality and maximum load, tensile strength at limit of proportionality and tensile strength at maximum load were calculated using the formula,

(a) Tensile stress at limit of proportionality (TS at LP) (kg cm^{-2}) = P/A

(b) Tensile stress at maximum load (TS at ML) (kg cm^{-2}) = P'/A

where

P = Load at limit of proportionately in kg

P' = Maximum load in kg

A = Cross sectional area of specimen in cm^2

3.2.6. Statistical analysis

The present study was an attempt to profile the palm wood properties and also to study the variation in wood properties of coconut palms from three different agro-climatic zones of Thrissur district. Samples were collected from these zones and within these zones, from three age groups. The sampling and subsampling gives rise to nested or hierarchical classification. Therefore, in this study, the model for analysis followed was NESTED ANOVA which was carried out using MINITAB (Ver. 17) and SPSS (Ver. 21).

RESULTS

IV. RESULTS

This chapter details the salient results of various tests conducted to analyse the coconut palm wood physical, anatomical and mechanical properties across three different age groups grown in three agro-climatic zones of Thrissur district, Kerala.

4.1. Coconut palm volume

Analysis of variance of coconut palm volume showed a significant difference between the age groups and there was no significant difference between the agro-climatic zones. Coconut palm volume for young palms ranged from 0.462 m^3 (Malayoram) to 0.571 m^3 (Coastal sandy), for matured palms from 0.551 m^3 (Central midland) to 0.566 m^3 (Coastal sandy) and for over mature palms ranges from 0.572 m^3 to 0.750 m^3 for Malayoram and Coastal sandy respectively (Table 2 and Figure 1).

4.2. Dermal to core wood ratio

The ratio between dermal wood to core wood was calculated for the sampled coconut palms across three different age groups (Table 2 and Figure 2). There was a significant difference in the dermal to core wood ratio across the age groups. The ratio valued zero and 8.00 for young palms and over mature palms respectively and averaged 6.38 for mature palms. The maximum value (8.00) was observed for over mature coconut palms while the minimum (zero) was observed in young coconut palms. There was no significant difference among agro-climatic zones.

4.2.3. Physical properties

The results obtained from the analysis of physical properties (basic density, oven dry density, moisture content, volumetric shrinkage, longitudinal shrinkage and dimensional shrinkage) of palm wood has been discussed below.

Table 2. Dermal to core wood ratio and volume of coconut palms from different agro-climatic zones and age groups

Dermal to Core wood (DC) ratio and Volume (m^3)							
Agro-climatic zones	Block	Age groups (years)					
		15-25		35-45		55-65	
		DC ratio	Volume (m^3)	DC ratio	Volume (m^3)	DC ratio	Volume (m^3)
Malayoram	1	0.00	0.49	8.00	0.60	8.00	0.74
	2	0.00	0.45	1.25	0.56	8.00	0.60
	3	0.00	0.41	1.25	0.51	8.00	0.53
	4	0.00	0.51	8.00	0.56	8.00	0.43
	Mean	0.00	0.46 (0.05)	4.63 (3.90)	0.56 (0.04)	8.00 (0.00)	0.57 (0.13)
Central midland	1	0.00	0.61	8.00	0.46	8.00	0.87
	2	0.00	0.44	8.00	0.65	8.00	0.85
	3	0.00	0.30	8.00	0.53	8.00	0.59
	4	0.00	0.46	8.00	0.65	8.00	0.47
	5	0.00	0.36	1.25	0.61	8.00	0.82
	6	0.00	0.46	8.00	0.53	8.00	0.65
	7	0.00	0.48	1.25	0.42	8.00	0.57
	8	0.00	0.48	8.00	0.56	8.00	0.58
	9	0.00	0.46	8.00	0.56	8.00	0.68
	Mean	0.00	0.45 (0.09)	6.50 (2.98)	0.55 (0.08)	8.00 (0.00)	0.67 (0.14)
Coastal sandy	1	0.00	0.56	8.00	0.61	8.00	0.94
	2	0.00	0.55	8.00	0.40	8.00	0.65
	3	0.00	0.56	8.00	0.61	8.00	0.69
	4	0.00	0.61	8.00	0.65	8.00	0.71
	Mean	0.00	0.57 (0.03)	8.00 (0.00)	0.57 (0.11)	8.00 (0.00)	0.75 (0.13)

Dermal to core wood ratio and volume of the palm are significant across age groups at 5% level; Value within parentheses is standard deviation (SD)

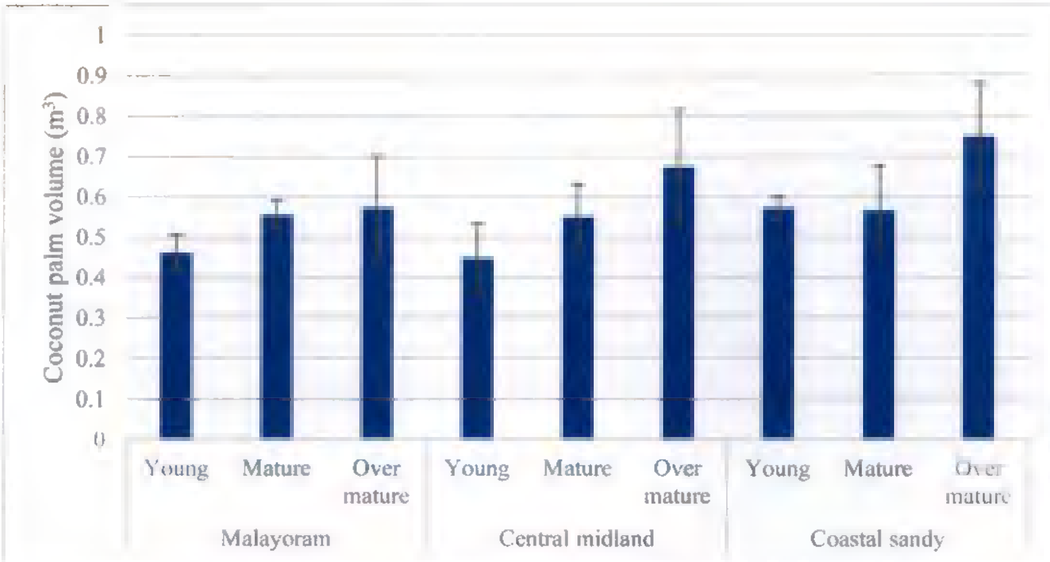

Figure 1. Volume of coconut palms from different agro-climatic zones and age

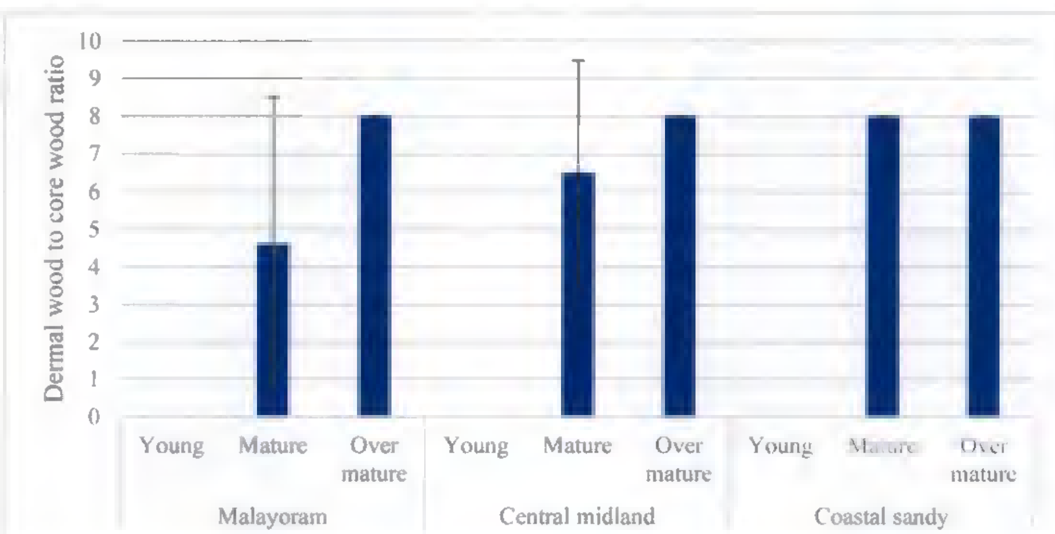

Figure 2. Dermal wood to core wood ratio of coconut palms from different agro-climatic zones and age groups

4.2.3.1. Basic density

The basic density ranged from 112.91 kg m^{-3} (core wood of young palms) to 826.44 kg m^{-3} (dermal wood of over mature palms) for Malayoram, 111.87 kg m^{-3} (core wood of young palms) to 869.88 kg m^{-3} (dermal wood of over mature palms) for Central midland and 114.20 kg m^{-3} (core wood of young palms) to 896.26 kg m^{-3} (dermal wood of over mature palms) for Coastal sandy. Analysis of variance conducted revealed that there was no significant difference in basic density between agro-climatic zones. The basic density for young palms ranged from 111.87 kg m^{-3} (core wood) to 323.05 kg m^{-3} (dermal wood), mature palms from 245.80 kg m^{-3} (core wood) to 776.58 kg m^{-3} (dermal wood) and over mature palm ranged from 340.50 kg m^{-3} (core wood) to 896.26 kg m^{-3} (dermal wood). There was a significant difference in density across age groups. Similarly, there was a significant difference across dermal, sub dermal and core wood in all agro-climatic zones and age groups (Table 3 and Figure 3).

4.2.3.2. Oven dry density

The oven dry density across three agro-climatic zones and age groups is tabulated (Table 4). The oven dry density ranged from (Figure 4.) 247.06 kg m^{-3} (core wood of young palms) to 812.34 kg m^{-3} (dermal wood of over mature palms) for Malayoram, 248.21 kg m^{-3} (core wood of young palms) to 954.53 kg m^{-3} (dermal wood of over mature palms) for Central midland and 201.82 kg m^{-3} (core wood of young palms) to 949.40 kg m^{-3} (dermal wood of over mature palms) for Coastal sandy. Oven dry density values from three agro-climatic zones did not show a significant difference. There was no significant difference in oven dry density within age groups and the value ranges from 201.82 kg m^{-3} (core wood) to 596.27 kg m^{-3} (dermal wood) for young palms, from 289.25 kg m^{-3} (core wood) to 703.63 kg m^{-3} (dermal wood) mature palms and from 333.28 kg m^{-3} (core wood) to 812.34 kg m^{-3} (dermal wood) over mature palm. The position of wood manifested a significant difference in all agro-climatic zones and age groups.

Table 3. Basic density of coconut palm wood from different agro-climatic zones and age groups

		Basic density (kg m^{-3})								
		Age groups (years)								
		15-25			35-45			55-65		
Agro-climatic zones	Block	Dermal	Sub dermal	Core	Dermal	Sub dermal	Core	Dermal	Sub dermal	Core
Malayoram	1	330.11 (43.77)	131.39 (34.49)	116.06 (7.45)	787.19 (9.83)	465.41 (30.42)	213.40 (6.18)	864.48 (43.00)	440.02 (95.81)	378.18 (41.50)
	2	277.50 (81.00)	115.47 (49.18)	107.91 (30.04)	639.45 (77.03)	374.77 (83.24)	296.98 (43.83)	913.10 (136.33)	597.75 (157.01)	348.75 (79.96)
	3	334.96 (88.40)	131.62 (97.59)	106.82 (8.17)	647.30 (29.23)	394.53 (58.53)	294.46 (30.30)	882.53 (51.82)	437.51 (8.42)	388.67 (15.34)
	4	310.18 (47.13)	128.96 (85.56)	120.87 (2.95)	654.77 (173.28)	491.45 (64.94)	178.35 (31.71)	645.66 (29.97)	469.35 (34.82)	246.40 (65.23)
	Mean	313.19 (26.10)	126.86 (7.69)	112.92 (6.72)	682.18 (70.29	431.54 (55.76)	245.80 (59.41)	826.44 (122.18)	486.16 (75.79	340.50 (64.97)
Central midland	1	285.17 (110.35)	133.75 (41.23)	112.58 (20.09)	646.31 (50.85)	508.32 (80.58)	251.46 (1.96)	880.63 (9.56)	570.59 (105.30)	396.84 (31.46)
	2	350.70 (66.48)	122.27 (47.05)	109.76 (20.03)	797.73 (62.59)	470.25 (60.06)	221.80 (13.39)	814.03 (7.66)	473.54 (119.73)	395.28 (49.23)
	3	363.02 (65.33)	133.30 (58.23)	115.88 (23.33)	750.60 (107.71)	455.81 (77.74)	333.49 (123.86)	932.01 (75.97)	594.55 (103.61)	399.39 (83.41)
	4	375.58 (7.88)	139.20 (31.05)	105.07 (26.54)	641.45 (76.28)	413.36 (162.22)	213.01 (15.28)	780.81 (14.76)	429.82 (84.20)	325.63 (24.67)

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Cont.

	5	382.80 (60.39)	158.44 (68.87)	116.99 (38.86)	637.78 (65.22)	374.22 (11.26)	301.11 (98.36)	917.33 (48.48)	563.12 (148.54)	372.63 (91.14)
	6	296.71 (74.26)	134.22 (45.33)	112.53 (12.33)	754.26 (87.68)	423.72 (77.94)	319.74 (27.69)	909.58 (39.04)	527.17 (86.38)	294.98 (11.03)
	7	334.45 (101.36)	140.36 (22.33)	119.86 (20.34)	645.36 (73.81)	370.91 (27.47)	237.13 (6.24)	891.33 (13.92)	428.83 (131.41)	288.23 (6.70)
	8	234.91 (76.71)	128.55 (84.36)	109.37 (43.76)	640.21 (47.78)	405.04 (18.47)	239.34 (22.53)	923.98 (14.29)	478.41 (149.88)	301.03 (90.22)
	9	258.96 (7.47)	122.58 (54.42)	104.80 (39.20)	851.44 (63.14)	568.90 (128.77)	226.22 (26.75)	779.25 (118.51)	572.08 (43.65)	355.73 (61.73)
	Mean	320.25 (53.33	134.74 (10.94)	111.87 (5.17)	707.24 (82.36)	443.39 (64.85)	260.37 (45.40)	869.88 (61.70)	515.35 (64.11)	347.75 (46.12)
Coastal sandy	1	310.18 (46.34)	131.96 (42.34)	103.87 (11.23)	777.26 (54.15)	438.89 (7.14)	203.00 (22.52)	920.22 (68.76)	478.53 (101.51)	364.92 (8.55)
	2	344.83 (8.75)	143.05 (44.34)	112.04 (7.30)	755.74 (132.37)	492.58 (129.25)	274.85 (22.80)	897.44 (100.93)	610.70 (89.73)	382.71 (20.66)
	3	325.35 (70.45)	133.30 (35.35)	111.88 (5.49)	784.74 (19.96)	494.23 (13.78)	293.35 (130.62)	876.76 (99.41)	558.86 (25.56)	332.82 (15.32)
	4	311.83 (33.12)	151.91 (58.27)	129.91 (3.02)	788.56 (112.90)	514.23 (29.69)	280.36 (16.99)	890.61 (74.54)	564.61 (29.22)	380.87 (43.33)
	Mean	323.05 (16.03)	140.06 (9.32)	114.42 (11.01)	776.58 (14.66)	484.98 (32.28)	262.89 (40.67)	896.26 (18.14)	553.18 (54.91)	365.33 (23.10)

Significant in age groups and between radial positions at 5% level; Value within parentheses is standard deviation (SD)

Table 4. Oven dry density of coconut palm wood from different agro-climatic zones and age groups

Agro-climatic zones	Block	Oven dry density (kg m^{-3}) Age groups (years) 15-25 Dermal	15-25 Sub dermal	15-25 Core	35-45 Dermal	35-45 Sub dermal	35-45 Core	55-65 Dermal	55-65 Sub dermal	55-65 Core
Malayoram	1	600.14	460.59	300.70	817.00	319.04	274.15	741.06	480.24	380.52
		(52.24)	(71.38)	(51.20)	(11.88)	(36.30)	(31.33)	(38.41)	(137.91)	(63.09)
	2	316.33	242.65	165.12	709.33	466.30	391.69	989.57	639.25	401.25
		(79.70)	(47.60)	(10.77)	(125.76)	(110.04)	(32.63)	(163.34)	(59.60)	(76.47)
	3	535.38	365.26	283.30	741.34	434.28	352.16	849.78	472.52	437.36
		(108.85)	(26.32)	(18.82)	(36.82)	(66.81)	(39.35)	(54.86)	(6.05)	(7.21)
	4	590.13	500.28	239.11	772.55	435.16	249.44	668.96	523.00	269.22
		(48.23)	(100.30)	(14.62)	(21.34)	(87.21)	(68.52)	(51.72)	(41.93)	(72.60)
	Mean	510.50	392.19	247.06	760.05	413.70	316.86	812.34	528.75	372.09
		(132.54)	(114.67)	(60.47)	(45.91)	(64.84)	(66.37)	(139.58)	(76.94)	(72.49
Central midland	1	687.91	535.35	422.55	737.78	628.97	325.15	698.00	593.00	324.09
		(106.82)	(21.47)	(87.22)	(49.92)	(72.81)	(15.23)	(32.69)	(120.91)	(55.16)
	2	672.14	405.46	257.34	781.01	434.02	265.62	921.55	490.25	402.37
		(93.44)	(52.47)	(43.03)	(72.09)	(71.06)	(14.87)	(8.53)	(143.01)	(31.37)
	3	547.58	365.84	225.48	786.85	411.36	411.50	1055.70	701.25	453.68
		(75.33)	(74.57)	(12.33)	(120.63)	(74.13)	(119.25)	(106.83)	(59.75)	(45.32)
	4	642.00	516.93	257.15	746.00	470.69	280.24	875.10	471.36	253.36
		(41.66)	(99.33)	(35.77)	(92.15)	(85.42)	(35.32)	(19.77)	(98.63)	(28.40)

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Cont.

	5	708.14 (66.31)	414.25 (80.02)	155.70 (56.33)	670.22 (12.34)	426.58 (45.33)	321.54 (1.56)	1088.30 (72.16)	745.58 (29.07)	486.53 (21.35)
	6	556.85 (75.55)	452.37 (12.67)	224.26 (41.34)	719.66 (106.90)	525.24 (40.39)	371.31 (30.10)	910.61 (49.81)	622.91 (91.45)	219.97 (12.22)
	7	531.40 (176.07)	462.14 (34.83)	199.35 (87.02)	701.25 (69.53)	397.42 (19.98)	237.76 (8.47)	985.35 (14.34)	472.96 (148.87)	304.13 (9.17)
	8	546.81 (85.81)	339.06 (102.80)	267.07 (26.40)	680.54 (50.97)	458.70 (17.37)	281.44 (23.26)	1072.94 (161.97)	425.68 (177.08)	286.60 (92.19)
	9	344.83 (9.89)	322.71 (74.33)	225.00 (45.32)	786.95 (69.82)	421.50 (136.30)	276.65 (38.65)	983.22 (7.20)	685.40 (68.11)	268.83 (61.34)
	Mean	581.96 (112.21)	423.79 (74.66)	248.21 (73.73)	734.47 (44.95)	463.83 (72.76)	307.91 (55.21)	954.53 (121.99)	578.71 (117.45)	333.28 (93.04)
Coastal sandy	1	590.13 (12.64)	500.28 (35.67)	239.11 (79.26)	618.78 (74.30)	252.37 (2.31)	214.00 (25.69)	1005.54 (89.34)	512.00 (30.26)	285.94 (10.49)
	2	578.55 (4.43)	502.33 (171.45)	191.83 (5.170	713.33 (146.31)	525.49 (182.57)	265.00 (31.64)	954.70 (122.32)	685.47 (115.04)	432.57 (18.29)
	3	577.00 (60.09)	348.67 (42.33)	210.23 (19.50)	785.41 (18.41)	555.80 (9.78)	374.52 (82.76)	941.02 (116.97)	621.37 (14.95)	262.09 (37.87)
	4	639.38 (24.20)	418.31 (61.36)	166.12 (6.61)	697.00 (71.01)	566.79 (33.56)	303.46 (30.97)	896.36 (141.89)	522.28 (27.67)	419.71 (47.06)
	Mean	596.27 (29.34)	442.40 (73.73)	201.82 (30.75)	703.63 (68.38)	475.11 (149.52)	289.25 (67.64)	949.40 (44.96)	585.28 (83.03)	350.08 (88.52)

Significant between radial positions at 5% level; Value within parentheses is standard deviation (SD)

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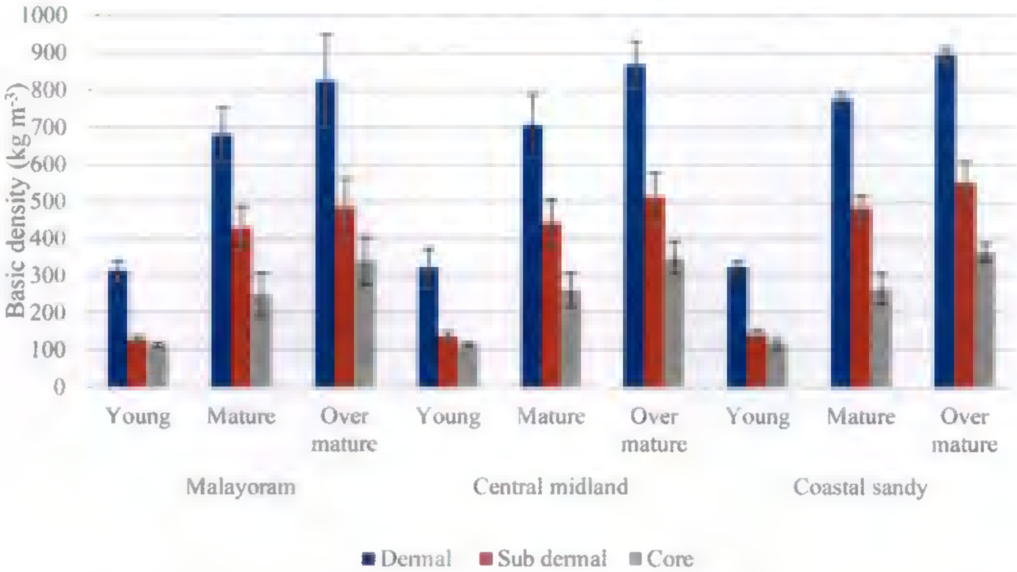

Figure 3. Basic density of coconut palm wood from different agro-climatic zones and age groups

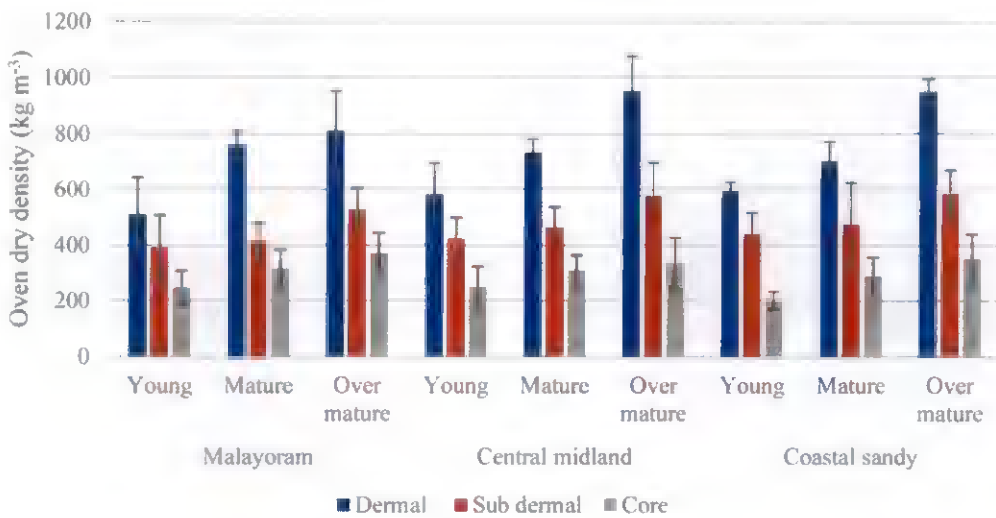

Figure 4. Oven dry density of coconut palm wood from different agro-climatic zones and age groups

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4.2.3.3. Moisture content

Analysis of variance for moisture content of coconut palm wood across three agro-climatic zones did not show significant difference, the values ranged from 47.26 % (dermal wood of over mature palms) to 401.90 % (core wood of young palms) for Malayoram, 34.70 % (dermal wood of over mature palms) to 328.59 % (core wood of young palms) for Central midland and 40.46 % (dermal wood of over mature palms) to 326.77 % (core wood of over mature palms) for Coastal sandy. However, moisture content was also found to be not significantly different across age groups. The moisture content ranged from 120.52 % (dermal wood) to 401.90 % (core wood) in young palms, 56.79 % (dermal wood) to 244.54 % (core wood) in mature palms and 34.70 % (dermal wood) to 172.25 % (core wood) in over mature palms. There was a significant difference across dermal, sub dermal and core wood in all agro-climatic zones and age groups as in Table 5 and Figure 5.

4.2.3.4. Volumetric shrinkage

The volumetric shrinkage ranged from 8.64 % (sub dermal wood of over mature palms) to 33.05 % (core wood of young palms) for Malayoram, 9.23 % (core wood of over mature palms) to 24.24 % (core wood of young palms) for Central midland and 9.25 % (sub dermal wood of mature palms) to 16.40 % (core wood of young palms) for Coastal sandy. Analysis of variance conducted revealed that there was no significant difference in volumetric shrinkage between agro-climatic zones and also between the age groups. The volumetric shrinkage across age groups ranged from 9.91 % (dermal wood) to 33.05 % (core wood) for young palms, 9.00 % (core wood) to 22.58 % (core wood) for mature palms and over mature palm ranged from 8.64 % (dermal wood) to 11.83 % (core wood). On contrary, there was a significant difference across dermal, sub dermal and core wood in all agro-climatic zones and age groups (Table 6 and Figure 6).

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Table 5. Moisture content of coconut palm wood from different agro-climatic zones and age groups

Agro-climatic zones	Block	Moisture content (%)								
		Age groups (years)								
		15-25			35-45			55-65		
		Dermal	Sub dermal	Core	Dermal	Sub dermal	Core	Dermal	Sub dermal	Core
Malayoram	1	148.48	228.83	422.24	67.31	259.08	359.64	52.24	66.31	149.29
		(28.11)	(13.24)	(13.55)	(1.73)	(25.98)	(9.72)	(8.19)	(67.84)	(42.47)
	2	233.04	265.03	620.10	73.93	170.93	207.89	38.31	65.30	175.05
		(52.26)	(85.89)	(63.10)	(11.68)	(48.72)	(51.85)	(10.15)	(13.51)	(33.45)
	3	144.87	162.73	229.72	66.94	92.38	144.61	49.77	100.14	141.17
		(31.96)	(64.92)	(31.42)	(5.79)	(38.60)	(44.30)	(7.16)	(11.33)	(10.42)
	4	163.03	168.44	335.56	75.89	84.37	266.01	48.71	151.19	223.50
		(14.39)	(30.20)	(89.86)	(60.02)	(47.89)	(83.63)	(4.06)	(12.19)	(76.09)
	Mean	172.35	206.26	401.90	71.01	151.69	244.54	47.26	95.73	172.25
		(41.21)	(49.29)	(165.40)	(4.57)	(81.55)	(91.36)	(6.15)	(40.36)	(37.09)
Central midland	1	140.09	166.24	312.22	69.61	108.42	296.51	47.49	75.36	137.19
		(7.35)	(26.19)	(45.54)	(10.51)	(16.69)	(2.06)	(6.98)	(20.63)	(33.46)
	2	149.93	158.66	321.82	59.04	98.33	248.76	26.00	65.72	132.44
		(14.67)	(18.13)	(53.71)	(7.14)	(23.88)	(56.92)	(1.98)	(36.63)	(32.79)
	3	159.17	211.04	279.33	53.43	148.94	213.21	25.15	53.44	80.65
		(16.33)	(25.23)	(61.23)	(9.17)	(62.30)	(73.29)	(2.58)	(16.62)	(18.79)
	4	146.94	224.85	345.49	46.82	130.17	234.71	48.26	142.79	230.43
		(4.46)	(15.37)	(61.67)	(3.56)	(91.32)	(57.54)	(1.76)	(34.41)	(28.78)

Cont.

	5	132.78 (14.49)	206.52 (42.86)	486.47 (66.18)	47.49 (1.26)	75.36 (5.37)	137.19 (18.33)	25.35 (8.91)	65.71 (46.69)	104.45 (56.87)
	6	175.69 (22.57)	202.83 (2.36)	306.59 (44.36)	76.56 (18.81)	141.54 (33.26)	203.81 (20.21)	49.75 (3.01)	89.57 (14.59)	127.34 (21.70)
	7	184.36 (17.29)	246.17 (22.47)	296.93 (10.12)	51.69 (1.05)	79.36 (8.22)	103.54 (6.87)	24.50 (3.08)	150.75 (55.72)	251.85 (7.08)
	8	197.78 (26.14)	213.43 (65.62)	288.84 (72.66)	68.31 (11.33)	190.92 (86.38)	330.92 (30.43)	38.29 (2.09)	135.86 (67.80)	239.71 (65.15)
	9	144.93 (17.76)	161.90 (32.13)	319.65 (33.26)	46.87 (1.06)	136.66 (51.15)	196.74 (26.59)	27.49 (5.68)	52.24 (5.36)	102.85 (13.08)
	Mean	159.08 (22.07)	199.07 (30.40)	328.59 (62.35)	57.76 (11.21)	123.30 (36.85)	218.38 (71.10)	34.70 (11.17)	92.38 (39.82)	156.32 (65.79)
Coastal sandy	1	99.36 (4.34)	128.44 (44.32)	309.23 (11.24)	60.69 (0.84)	159.16 (5.01)	202.26 (84.83)	33.17 (5.33)	96.42 (43.19)	179.28 (11.31)
	2	189.32 (82.91)	267.24 (97.40)	400.18 (67.64)	50.05 (17.20)	63.03 (34.57)	126.97 (20.03)	61.30 (16.60)	75.48 (23.14)	110.00 (10.78)
	3	93.84 (7.38)	114.04 (24.47)	285.99 (7.45)	70.21 (4.045)	95.94 (19.86)	118.77 (15.15)	28.04 (9.96)	72.54 (8.76)	127.29 (14.00)
	4	99.56 (10.51)	142.09 (22.05)	311.67 (23.26)	46.22 (6.70)	71.15 (22.60)	121.90 (24.13)	39.34 (13.34)	89.15 (6.52)	95.36 (7.01)
	Mean	120.52 (45.95)	162.95 (70.46)	326.77 (50.29)	56.79 (10.84)	97.32 (43.54)	142.47 (40.00)	40.46 (14.64)	83.40 (11.30)	127.98 (36.61)

Significant between radial positions at 5%; Value within parentheses is standard deviation (SD)

Table 6. Volumetric shrinkage of coconut palm wood from different agro-climatic zones and age groups

Volumetric shrinkage (%)										
Agro-climatic zones	Block	Age groups (years)								
		15-25			35-45			55-65		
		Dermal	Sub dermal	Core	Dermal	Sub dermal	Core	Dermal	Sub dermal	Core
Malayoram	1	11.55	15.08	61.69	15.88	16.79	21.66	9.15	3.36	8.24
		(4.30)	(8.85)	(2.69)	(1.61)	(1.91)	(4.73)	(0.63)	(2.24)	(2.41)
	2	12.88	11.59	35.21	15.28	21.93	25.44	11.69	10.06	11.32
		(4.20)	(3.38)	(1.63)	(1.43)	(3.39)	(4.95)	(1.23)	(1.24)	(2.72)
	3	14.92	12.32	6.90	12.28	9.10	16.33	11.46	10.93	11.15
		(1.11)	(2.08)	(0.89)	(0.43)	(0.54)	(0.91)	(0.40)	(0.70)	(2.43)
	4	13.55	11.59	28.41	19.17	14.98	26.90	7.82	10.23	8.40
		(3.77)	(2.00)	(3.34)	(3.04)	(1.65)	(5.55)	(2.91)	(0.55)	(0.87)
	Mean	13.23	12.64	33.05	15.65	15.70	22.58	10.03	8.64	9.78
		(1.40)	(1.66)	(22.59)	(2.83)	(5.29)	(4.72)	(1.87)	(3.54)	(1.69)
Central midland	1	12.16	15.34	44.97	9.29	19.50	60.09	6.46	2.80	8.38
		(2.08)	(3.82)	(4.61)	(3.44)	(4.00)	(0.62)	(3.39)	(0.62)	(3.29)
	2	12.06	13.15	24.60	11.94	14.66	16.40	11.67	9.14	3.69
		(2.43)	(0.42)	(4.53)	(0.57)	(1.57)	(5.08)	(0.11)	(2.46)	(1.30)
	3	12.33	13.61	16.05	11.69	13.95	20.11	11.59	12.74	10.33
		(2.45)	(1.33)	(4.32)	(0.42)	(3.94)	(7.44)	(1.94)	(3.48)	(4.39)
	4	14.98	24.93	20.06	11.43	12.13	23.20	10.77	8.65	10.92
		(3.91)	(6.09)	(4.67)	(1.01)	(0.35)	(4.61)	(0.36)	(1.22)	(1.70)

Cont.

	5	13.64	13.44	18.58	8.90	14.83	16.69	12.95	11.47	10.80
		(0.42)	(1.13)	(4.26)	(1.24)	(2.66)	(0.99)	(1.31)	(1.98)	(0.72)
	6	12.24	14.83	29.02	11.54	19.61	13.88	14.37	15.52	6.80
		(2.33)	(1.25)	(3.66)	(2.24)	(2.64)	(2.83)	(0.52)	(1.64)	(1.17)
	7	14.47	15.01	17.69	12.18	8.20	5.23	13.66	9.19	18.37
		(8.52)	(2.97)	(7.00)	(1.30)	(1.38)	(2.32)	(0.38)	(1.78)	(1.65)
	8	13.18	17.84	21.75	11.92	11.71	14.99	12.95	10.09	8.73
		(1.41)	(0.04)	(2.34)	(0.35)	(1.38)	(2.89)	(3.63)	(1.69)	(1.55)
	9	12.72	7.02	25.44	9.71	11.87	18.04	12.05	11.91	5.07
		(2.09)	(4.27)	(4.98)	(0.06)	(2.18)	(2.65)	(2.98)	(1.59)	(2.92)
	Mean	13.09	15.02	24.24	10.96	14.05	20.96	11.83	10.17	9.23
		(1.07)	(4.72)	(8.80)	(1.28)	(3.70)	(15.48)	(2.30)	(3.51)	(4.25)
Coastal sandy	1	8.29	10.65	14.33	5.41	5.35	7.72	10.40	6.29	7.34
		(2.66)	(2.99)	(4.33)	(3.85)	(1.97)	(3.10)	(1.18)	(2.91)	(0.70)
	2	9.97	12.03	31.12	10.80	9.37	4.59	11.58	11.61	11.37
		(2.10)	(1.85)	(4.57)	(2.01)	(2.49)	(2.22)	(0.89)	(2.12)	(1.33)
	3	12.33	11.94	8.05	12.82	11.09	16.46	12.57	10.06	14.66
		(2.75)	(3.01)	(2.42)	(0.87)	(0.95)	(4.26)	(0.43)	(3.64)	(4.80)
	4	9.04	8.16	12.12	10.16	11.20	7.24	10.22	11.07	9.27
		(1.72)	(0.45)	(1.84)	(1.19)	(5.55)	(8.79)	(8.35)	(1.18)	(0.60)
	Mean	9.91	10.70	16.40	9.80	9.25	9.00	11.19	9.76	10.66
		(1.75)	(1.80)	(10.15)	(3.14)	(2.73)	(5.16)	(1.10)	(2.40)	(3.13)

Significant between radial positions at 5% level; Value within parentheses is standard deviation (SD)

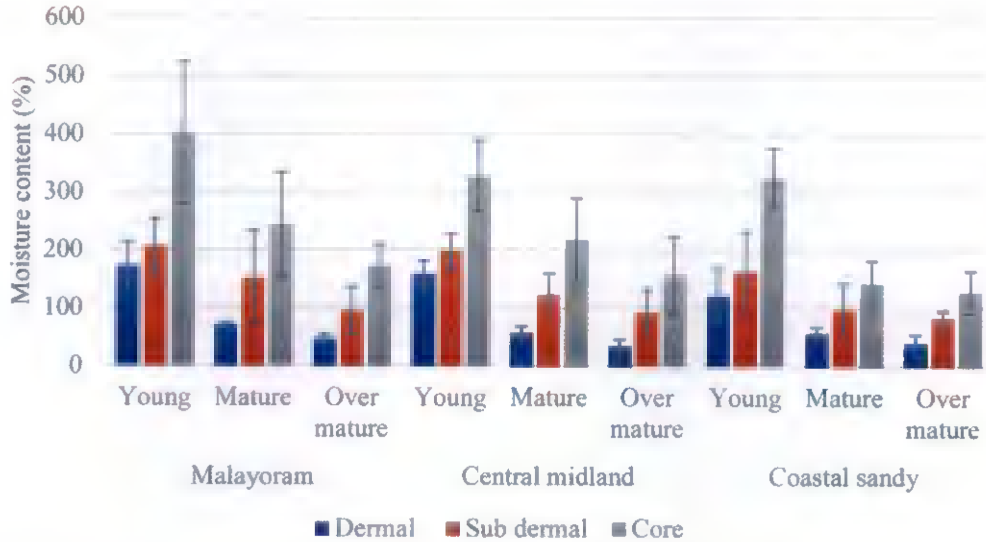

Figure 5. Moisture content of coconut palm wood from different agro-climatic zones and age groups

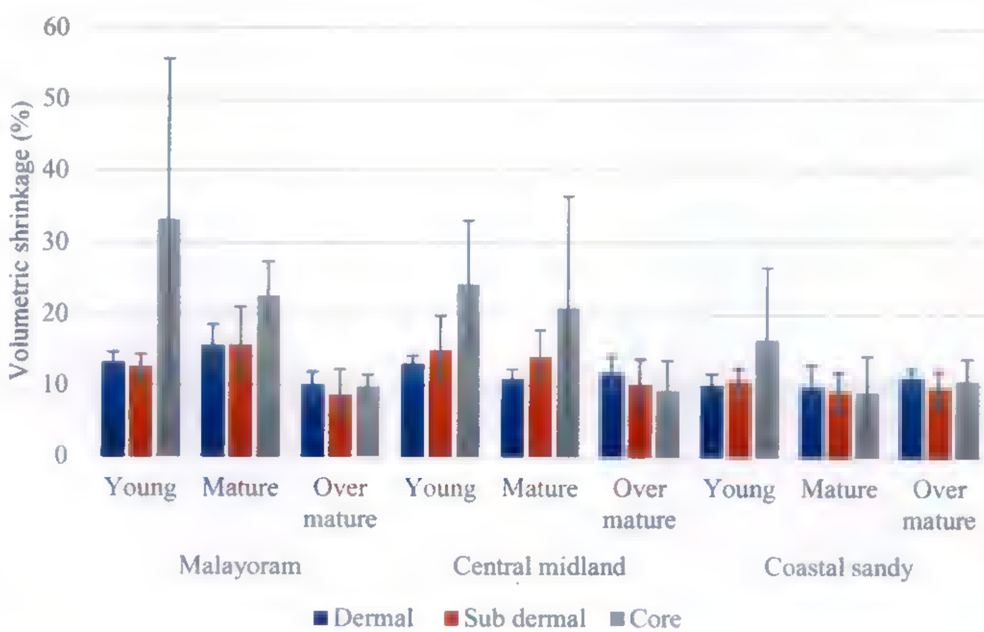

Figure 6. Volumetric shrinkage of coconut palm wood from different agro-climatic zones and age groups

4.2.3.5. Longitudinal shrinkage

The longitudinal shrinkage ranged from 0.50 % (dermal wood of over mature palms) to 2.93 % (core wood of young palms) for Malayoram, 0.55 % (core wood of young palms) to 2.35 % (core wood of young palms) for Central midland and 0.28 % (dermal wood of mature palms) to 1.50 % (core wood of over mature palms) for Coastal sandy (Figure 7). Analysis of variance conducted revealed that there was no significant difference in longitudinal shrinkage between agro-climatic zones. The longitudinal shrinkage for young palms ranged from 0.47 % (dermal wood) to 2.93 % (core wood), mature palms ranged from 0.28 % (dermal wood) to 2.35 % (core wood) and over mature palm ranged from 0.41 % (dermal wood) to 1.50 % (core wood). There was no significant difference in longitudinal shrinkage across age groups. Contrary, there was a significant difference across dermal, sub dermal and core wood in all agro-climatic zones and age groups (Table 7).

4.2.3.6. Dimensional shrinkage

The dimensional shrinkage ranged from 3.70 % (dermal wood of young palms) to 14.34 % (core wood of young palms) for Malayoram, 3.68 % (dermal wood of young palms) to 9.93 % (core wood of young palms) for Central midland and 2.57 % (dermal wood of mature palms) to 8.17 % (core wood of young palms) for Coastal sandy (Figure 8). Analysis of variance conducted revealed that there was no significant difference in dimensional shrinkage between agro-climatic zones. Thereupon dimensional shrinkage for young palms ranged from 3.70 % (dermal wood) to 14.34 % (core wood), mature palms ranged from 2.57 % (dermal wood) to 9.90 % (core wood) and over mature palm ranged from 3.68 % (dermal wood) to 6.68 % (core wood). There was no significant difference in dimensional shrinkage across age groups. Contrarily, there was a significant difference in dimensional shrinkage across dermal, sub dermal and core wood in all agro-climatic zones and age groups (Table 8).

Table 7. Longitudinal shrinkage of coconut palm wood from different agro-climatic zones and age groups

Agro-climatic zones	Block	Longitudinal shrinkage (%) Age groups (years) 15-25 Dermal	15-25 Sub dermal	15-25 Core	35-45 Dermal	35-45 Sub dermal	35-45 Core	55-65 Dermal	55-65 Sub dermal	55-65 Core
Malayoram	1	0.26 (0.09)	1.24 (0.37)	1.67 (0.81)	0.45 (0.28)	0.58 (0.21)	0.89 (0.21)	0.24 (0.19)	0.49 (0.24)	0.85 (0.64)
	2	0.61 (0.38)	0.99 (0.57)	3.12 (0.93)	0.45 (0.18)	0.55 (0.20)	0.94 (0.43)	0.48 (0.19)	1.57 (0.55)	1.85 (0.76)
	3	2.76 (0.14)	3.22 (0.87)	5.87 (1.99)	0.83 (0.13)	1.17 (0.15)	1.50 (0.37)	0.95 (0.54)	1.03 (0.15)	1.49 (0.73)
	4	0.35 (0.19)	0.39 (0.26)	1.06 (0.60)	0.77 (0.57)	3.84 (0.52)	6.06 (1.28)	0.34 (0.13)	0.68 (0.35)	0.81 (0.31)
	Mean	1.00 (1.19)	1.46 (1.22)	2.93 (2.14)	0.63 (0.20)	1.53 (1.56)	2.35 (2.49)	0.50 (0.32)	0.94 (0.48)	1.25 (0.51)
Central midland	1	0.41 (0.21)	0.85 (0.35)	1.33 (0.67)	0.44 (0.19)	0.60 (0.29)	0.90 (0.35)	0.43 (0.19)	1.26 (0.21)	1.89 (0.53)
	2	0.34 (0.14)	0.71 (0.04)	1.11 (0.23)	0.24 (0.18)	0.31 (0.02)	1.42 (0.99)	0.67 (0.14)	0.71 (0.23)	0.86 (0.46)
	3	0.35 (0.03)	0.47 (0.21)	0.77 (0.25)	0.61 (0.48)	1.82 (0.08)	2.11 (0.75)	0.29 (0.01)	0.44 (0.30)	0.46 (0.20)
	4	0.60 (0.23)	0.63 (0.18)	1.15 (0.45)	0.33 (0.11)	0.85 (0.23)	1.59 (0.42)	0.19 (0.02)	0.38 (0.19)	0.72 (0.11)

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Cont.

	5	3.40 (0.41)	3.60 (0.81)	7.69 (0.71)	0.62 (0.10)	0.98 (0.24)	1.12 (0.92)	0.36 (0.05)	0.50 (0.13)	0.82 (0.19)
	6	1.75 (0.37)	2.87 (0.26)	3.54 (1.12)	0.12 (0.08)	0.54 (0.12)	0.77 (0.17)	0.28 (0.17)	0.46 (0.25)	0.50 (0.06)
	7	0.98 (0.04)	1.12 (0.02)	2.19 (0.69)	0.20 (0.10)	0.49 (0.16)	0.56 (0.29)	0.79 (0.04)	1.26 (0.53)	1.45 (0.72)
	8	0.36 (0.45)	0.51 (0.18)	0.66 (0.15)	2.43 (0.07)	2.84 (0.52)	4.23 (0.45)	0.98 (0.64)	1.13 (0.44)	3.46 (0.84)
	9	0.45 (0.05)	0.96 (0.34)	2.69 (0.43)	0.77 (0.24)	0.46 (0.22)	0.33 (0.06)	1.00 (0.48)	1.08 (0.29)	3.04 (0.36)
	Mean	0.96 (1.02)	1.30 (1.13)	2.35 (2.22)	0.66 (0.75)	1.04 (0.87	1.51 (1.24)	0.55 (0.31)	0.80 (0.38)	1.47 (1.11)
Coastal sandy	1	0.35 (0.10)	0.39 (0.13)	1.06 (0.55)	0.22 (0.12)	0.39 (0.17)	0.66 (0.36)	0.54 (0.26)	0.58 (0.26)	0.74 (0.48)
	2	0.88 (0.02)	1.03 (0.47)	1.20 (0.69)	0.15 (0.14)	0.27 (0.20)	0.49 (0.20)	0.35 (0.06)	1.51 (0.20)	2.46 (0.18)
	3	0.35 (0.22)	0.47 (0.28)	0.77 (0.34)	0.29 (0.12)	0.37 (0.03)	0.47 (0.15)	0.52 (0.17)	1.02 (0.30)	1.81 (0.06)
	4	0.31 (0.06)	0.84 (0.04)	1.90 (0.58)	0.47 (0.13)	0.84 (0.25)	1.08 (0.30)	0.23 (0.07)	0.57 (0.22)	1.00 (0.03)
	Mean	0.47 (0.27)	0.68 (0.30)	1.23 (0.48)	0.28 (0.14)	0.47 (0.25)	0.68 (0.28)	0.41 (0.15)	0.92 (0.44)	1.50 (0.78)

Significant between radial positions at 5% level; Value within parentheses is standard deviation (SD)

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Table 8. Dimensional shrinkage of coconut palm wood from different agro-climatic zones and age groups

Agro-climatic zones	Block	Dimensional shrinkage (%)								
		Age groups (years)								
		15-25			35-45			55-65		
		Dermal	Sub dermal	Core	Dermal	Sub dermal	Core	Dermal	Sub dermal	Core
Malayoram	1	3.48 (1.78)	4.95 (1.79)	34.41 (1.44)	4.52 (1.06)	5.39 (0.94)	5.73 (2.41)	4.62 (0.25)	5.40 (2.85)	6.23 (1.11)
	2	3.60 (2.65)	4.40 (1.24)	13.49 (4.78)	7.49 (1.22)	11.39 (1.80)	13.48 (2.69)	5.73 (0.81)	6.07 (0.40)	7.03 (0.38)
	3	3.69 (1.08)	4.01 (1.11)	4.36 (1.00)	2.85 (0.34)	4.16 (1.25)	4.92 (0.43)	5.21 (0.85)	5.44 (0.88)	7.75 (1.91)
	4	4.046 (0.72)	4.98 (1.41)	5.09 (2.74)	4.88 (0.27)	11.41 (2.16)	11.99 (4.32)	4.57 (1.45)	4.85 (0.55)	5.20 (1.35)
	Mean	3.70 (0.25)	4.58 (0.47)	14.34 (14.01)	4.94 (1.92)	8.09 (3.86)	9.03 (4.34)	5.03 (0.55)	5.44 (0.50)	6.55 (1.09)
Central midland	1	6.14 (0.87)	6.44 (1.87)	22.78 (5.87)	4.47 (0.40)	9.99 (1.38)	37.09 (0.41)	2.41 (0.41)	2.79 (0.47)	4.48 (0.45)
	2	5.01 (0.80)	5.30 (1.29)	12.42 (0.82)	5.63 (1.04)	5.15 (1.23)	4.64 (3.15)	4.09 (1.41)	4.12 (0.19)	5.48 (0.60)
	3	4.05 (0.12)	6.13 (0.93)	6.50 (2.11)	3.74 (0.56)	4.83 (1.02)	6.40 (1.25)	3.78 (0.45)	5.06 (0.59)	5.39 (1.31)
	4	4.77 (0.88)	6.59 (1.60)	6.95 (0.66)	5.24 (0.63)	5.36 (0.99)	12.99 (2.02)	3.55 (0.55)	4.32 (0.88)	4.82 (0.67)

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Cont.

	5	3.43	5.85	7.20	1.75	1.87	2.15	3.78	5.73	5.93
		(0.86)	(0.59)	(2.43)	(0.66)	(0.33)	(1.24)	(1.03)	(0.49)	(1.31)
	6	5.42	4.80	9.04	4.07	4.44	5.47	1.28	6.80	7.64
		(1.69)	(0.66)	(2.34)	(0.84)	(1.44)	(0.12)	(0.99)	(1.27)	(0.03)
	7	1.75	1.87	3.54	2.83	4.19	6.06	5.33	5.50	6.94
		(0.22)	(0.17)	(1.17)	(0.79)	(0.75)	(1.14)	(0.51)	(1.20)	(0.56)
	8	6.15	6.90	7.45	4.34	4.49	7.77	4.88	5.33	9.32
		(1.37)	(1.17)	(1.43)	(1.36)	(0.38)	(1.12)	(0.53)	(0.30)	(0.21)
	9	3.17	5.31	13.48	1.28	4.80	6.49	4.02	4.85	7.37
		(0.97)	(1.11)	(2.69)	(0.10)	(1.09)	(1.03)	(0.90)	(0.64)	(1.39)
	Mean	4.43	5.47	9.93	3.71	5.01	9.90	3.68	4.94	6.37
		(1.47)	(1.51)	(5.70)	(1.49)	(2.13)	(10.60)	(1.22)	(1.13)	(1.57)
Coastal sandy	1	4.05	4.98	5.09	1.86	2.04	4.16	5.17	5.55	6.29
		(1.12)	(1.48)	(1.93)	(0.24)	(1.00)	(0.73)	(1.23)	(1.13)	(0.44)
	2	3.76	3.95	15.94	2.25	4.57	5.56	5.14	6.57	9.55
		(0.53)	(0.55)	(2.82)	(1.17)	(1.34)	(1.07)	(1.79)	(0.65)	(0.89)
	3	4.05	6.13	6.50	2.66	5.24	5.64	7.11	6.04	5.14
		(0.64)	(0.38)	(1.01)	(0.39)	(0.67)	(0.79)	(0.91)	(2.61)	(1.01)
	4	3.87	4.75	5.16	3.52	8.30	8.93	3.62	3.98	5.73
		(0.88)	(0.45)	(1.58)	(0.38)	(0.24)	(1.90)	(1.48)	(0.43)	(0.92)
	Mean	3.93	4.95	8.17	2.57	5.04	6.07	5.26	5.54	6.68
		(0.14)	(0.90)	(5.22)	(0.71)	(2.58)	(2.02)	(1.43)	(1.12)	(1.98)

Significant between radial positions at 5%; Value within parentheses is standard deviation

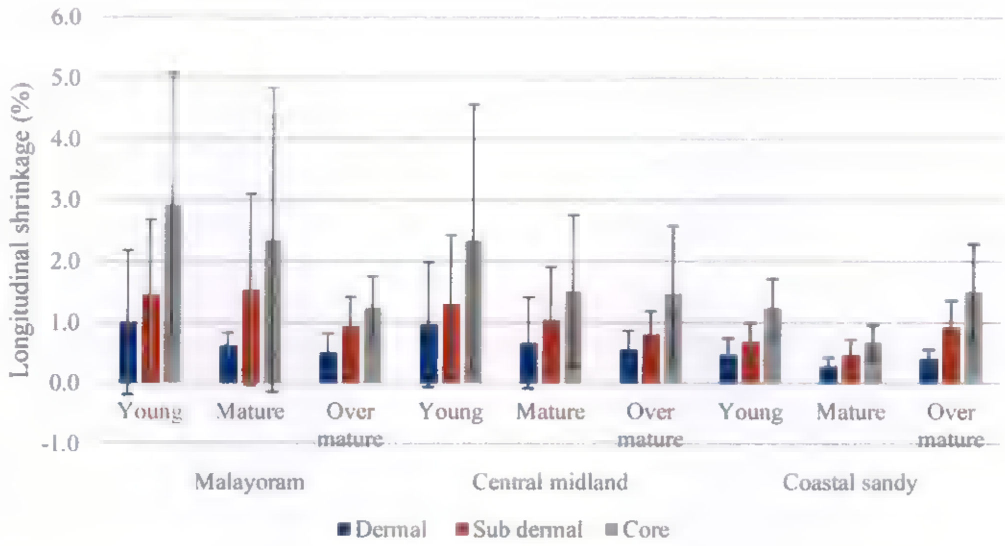

Figure 7. Longitudinal shrinkage of coconut palm wood from different agro-climatic zones and age groups

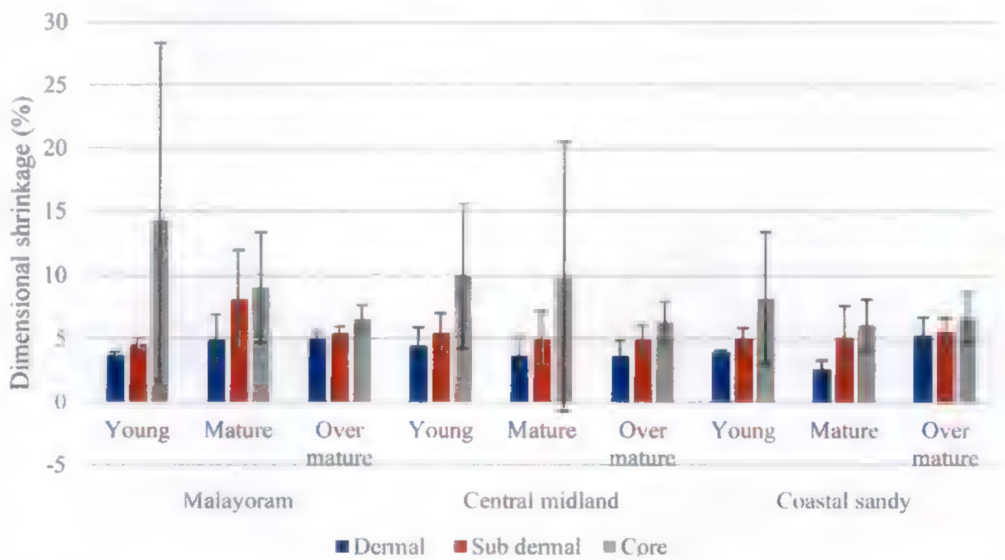

Figure 8. Dimensional shrinkage of coconut palm wood from different agro-climatic zones and age groups

Table 9. Vascular bundle frequency of coconut palm wood from different agro-climatic zones and age groups

Agro-climatic zones	Block	Vascular bundle frequency (per sq. cm) — Age groups (years) 15-25			35-45			55-65		
		Dermal	Sub dermal	Core	Dermal	Sub dermal	Core	Dermal	Sub dermal	Core
Malayoram	1	50.67 (4.73)	35.00 (7.00)	20.33 (9.29)	60.67 (5.51)	38.33 (3.22)	19.33 (0.58)	48.67 (1.16)	40.33 (12.12)	33.33 (4.16)
	2	50.00 (11.27)	31.67 (4.73)	18.33 (8.51)	45.33 (6.43)	32.33 (5.51)	16.33 (2.31)	52.33 (6.51)	40.00 (3.61)	21.67 (6.51)
	3	55.00 (2.00)	35.67 (10.21)	21.67 (6.43)	75.67 (5.03)	45.67 (3.51)	43.67 (11.59)	92.33 (3.79)	44.33 (3.79)	33.67 (2.52)
	4	48.00 (7.21)	32.00 (8.89)	19.33 (2.08)	49.67 (7.51)	31.00 (5.57)	16.00 (2.65)	92.33 (11.24)	40.67 (5.51)	27.00 (3.46)
	Mean	50.92 (2.95)	33.58 (2.04)	19.92 (1.42)	57.83 (13.53)	36.83 (6.70)	23.83 (13.31)	71.42 (24.20)	41.33 (2.02)	28.92 (5.72)
Central midland	1	50.20 (28.54)	38.70 (6.43)	25.00 (4.58)	78.67 (4.04)	55.67 (6.03)	42.67 (1.53)	62.33 (24.85)	49.33 (7.10)	30.33 (3.79)
	2	56.00 (3.61)	45.00 (6.25)	23.67 (0.58)	42.33 (2.08)	30.33 (1.53)	15.67 (1.53)	84.67 (3.51)	40.00 (5.29)	23.33 (6.43)
	3	44.33 (5.33)	28.00 (8.32)	10.67 (2.56)	68.00 (2.65)	35.00 (5.00)	19.33 (0.58)	93.67 (5.13)	83.33 (14.84)	35.00 (7.94)
	4	55.00 (1.53)	31.00 (9.29)	20.33 (0.58)	53.67 (2.52)	34.67 (3.06)	20.00 (9.17	60.67 (4.16)	37.67 (16.56)	15.00 (6.08)

Cont.

	5	50.00 (4.36)	37.00 (6.25)	21.00 (1.73)	48.33 (7.33)	29.67 (1.23)	14.00 (4.34)	57.00 (9.85)	36.67 (14.01)	28.33 (11.68)
	6	42.67 (1.33)	19.67 (2.11)	14.00 (0.26)	50.33 (6.66)	39.00 (12.00)	20.33 (6.66)	597.00 (9.54)	50.67 (3.51)	23.67 (4.51)
	7	48.30 (3.51)	19.70 (2.08)	14.00 (2.00)	57.30 (22.50)	33.00 (2.65)	17.67 (2.08)	77.33 (15.31)	31.67 (3.51)	14.67 (2.08)
	8	57.33 (6.03)	37.33 (14.05)	21.67 (2.52)	41.33 (3.06)	31.67 (4.51)	14.67 (3.06)	68.00 (1.00)	28.00 (9.00)	22.67 (6.35)
	9	58.33 (3.22)	40.67 (4.04)	27.00 (5.29)	52.30 (2.52)	30.30 (9.87)	23.70 (4.51)	67.00 (16.64)	38.33 (3.22)	19.67 (5.51)
	Mean	51.35 (5.66)	33.01 (9.04)	19.70 (5.59)	54.70 (12.02)	35.48 (8.13)	20.89 (8.73)	69.74 (12.87)	43.96 (16.47)	23.63 (6.78)
Coastal sandy	1	62.00 (2.48)	37.00 (6.56)	19.33 (4.33)	50.67 (14.74)	27.33 (4.04)	21.33 (5.03)	59.33 (6.51)	44.00 (12.12)	27.00 (4.58)
	2	44.67 (14.22)	40.67 (4.93)	14.67 (1.16)	78.00 (12.01)	44.67 (2.52)	28.67 (15.31)	65.00 (4.36)	43.00 (14.73)	29.33 (5.51)
	3	44.33 (4.04)	28.00 (3.00)	10.67 (2.08)	71.33 (4.16)	43.33 (8.62)	28.67 (7.64)	84.33 (12.34)	42.00 (3.61)	14.33 (2.52)
	4	59.33 (8.08)	21.00 (3.61)	10.33 (1.16)	45.00 (7.55)	35.33 (1.53)	14.33 (0.58)	73.00 (2.65)	47.33 (9.03)	42.67 (6.51)
	Mean	52.58 (9.40)	31.67 (8.88)	13.75 (4.21)	61.25 (15.90)	37.67 (8.03)	23.25 (6.88)	70.42 (10.84)	44.08 (2.32)	28.33 (11.61)

Significant between radial positions at 5% level; Value within parentheses is standard deviation (SD)

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Table 10. Vascular bundle sheath thickness of coconut palm wood from different agro-climatic zones and age groups

Agro-climatic zones	Block	Vascular bundle sheath thickness (µm)								
		Age groups (years)								
		15-25			35-45			55-65		
		Dermal	Sub dermal	Core	Dermal	Sub dermal	Core	Dermal	Sub dermal	Core
Malayoram	1	1047.43 (96.78)	870.73 (146.45)	611.37 (82.51)	1555.00 (120.66)	965.65 (214.33)	822.00 (201.23)	1124.50 (184.32)	912.40 (78.32)	755.65 (98.32)
	2	1145.85 (97.23)	854.50 (142.36)	732.54 (153.69)	1095.50 (201.58)	865.45 (111.48)	656.45 (222.79)	938.72 (170.63)	593.11 (126.65)	398.51 (116.33)
	3	517.85 (109.11)	512.54 (111.36)	510.88 (109.77)	571.07 (121.47)	454.66 (84.99)	450.05 (71.02)	545.00 (195.48)	486.56 (132.52)	435.40 (147.33)
	4	911.54 (85.37)	745.92 (76.23)	654.50 (45.96)	1002.75 (257.50)	706.91 (122.93)	658.45 (214.37)	1225.80 (120.86)	985.42 (96.15)	865.95 (85.25)
	Mean	905.67 (275.81)	745.92 (165.16)	627.32 (92.42)	1056.08 (403.55)	748.17 (222.79)	646.74 (152.35)	958.51 (300.21)	744.37 (241.99)	613.88 (232.29)
Central midland	1	1354.00 (124.86)	954.54 (49.23)	765.60 (122.85)	773.01 (90.47)	556.98 (76.83)	514.11 (91.87)	795.00 (203.26)	549.00 (111.26)	455.00 (108.37)
	2	1254.58 (85.67)	988.84 (97.26)	845.40 (164.55)	1121.50 (112.33)	895.64 (74.67)	784.56 (161.58)	956.56 (77.46)	658.40 (55.55)	458.40 (98.66)
	3	965.44 (47.67)	898.80 (122.48)	754.00 (145.22)	1214.70 (124.68)	911.02 (177.93)	857.24 (112.46)	954.65 (141.20)	857.99 (229.05)	622.35 (115.45)
	4	1054.00 (122.66)	956.56 (86.12)	756.54 (145.96)	1154.50 (59.57)	954.50 (66.52)	656.45 (62.13)	775.03 (144.01)	679.06 (65.20)	548.71 (82.82)

87

Cont.

	5	1254.54 (144.66)	1254.50 (74.33)	954.56 (132.55)	995.65 (74.67)	854.65 (74.52)	425.46 (119.65)	1177.70 (144.33)	968.85 (141.56)	814.55 (71.55)
	6	1238.85 (83.22)	1154.74 (66.15)	784.56 (122.46)	1154.50 (223.58)	891.32 (125.12)	766.56 (127.63)	725.40 (86.16)	676.56 (74.66)	654.54 (162.66)
	7	1145.40 (88.66)	1045.50 (68.57)	951.51 (176.11)	1244.00 (146.84)	1025.85 (148.67)	854.45 (73.52)	1066.00 (149.51)	932.25 (114.33)	865.45 (142.55)
	8	1074.80 (117.66)	956.54 (122.84)	865.90 (95.67)	1025.50 (78.56)	954.50 (161.57)	754.40 (127.85)	945.30 (217.55)	866.56 (200.75)	715.45 (145.66)
	9	964.50 (99.61)	784.50 (100.54)	556.18 (77.13)	1072.02 (197.21)	874.55 (242.28)	795.38 (202.55)	1155.40 (141.07)	848.29 (72.30)	492.67 (167.66)
	Mean	1145.12 (138.98)	999.39 (138.49)	803.81 (121.45)	1083.93 (142.36)	879.89 (131.68)	712.07 (151.13)	950.12 (163.04)	781.88 (144.09)	625.24 (151.16)
Coastal sandy	1	1215.45 (121.75)	1125.00 (163.49)	954.56 (214.46)	1125.40 (114.48)	1011.51 (132.85)	912.50 (155.45)	1011.40 (142.45)	912.45 (88.13)	845.42 (117.60)
	2	954.54 (72.66)	766.71 (136.50)	756.60 (221.96)	765.98 (106.86)	549.74 (80.37)	479.90 (133.57)	788.91 (182.30)	689.70 (173.36)	683.79 (203.45)
	3	965.55 (151.44)	896.650 (163.85)	826.82 (207.42)	912.47 (96.34)	879.04 (183.52)	719.63 (167.55)	1191.15 (232.56)	1023.45 (59.56)	891.51 (115.56)
	4	1255.40 (207.33)	835.54 (129.56)	754.80 (153.25)	956.57 (116.56)	758.45 (200.45)	658.00 (94.55)	896.56 (97.70)	812.45 (95.48)	580.08 (143.67)
	Mean	1097.73 (159.89)	905.97 (155.37)	823.19 (93.78)	940.10 (147.97)	799.69 (196.08)	692.51 (178.44)	972.00 (172.04)	859.51 (142.28)	750.20 (144.21)

Significant between radial positions at 5% level; Value within parentheses is standard deviation (SD)

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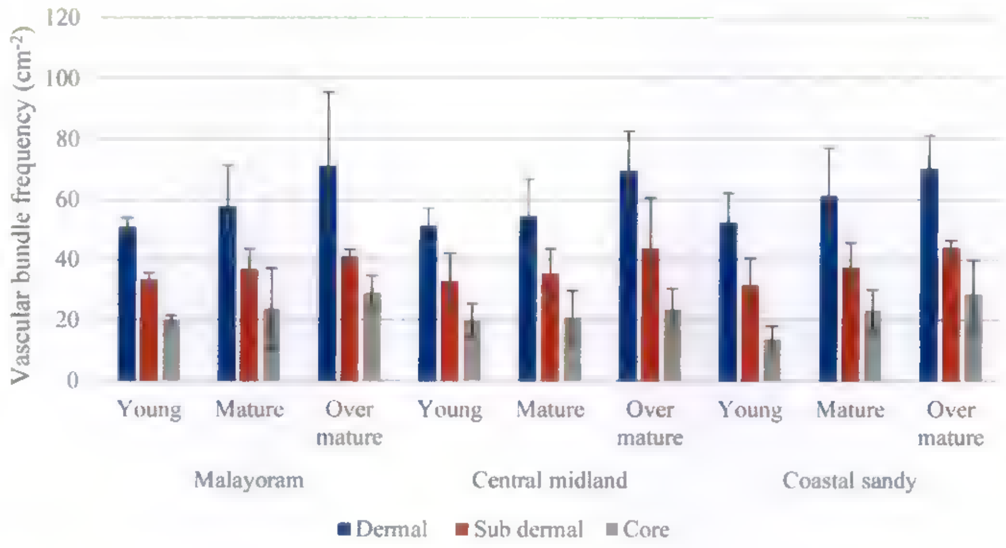

Figure 9. Vascular bundle frequency of coconut palm wood from different agro-climatic zones and age groups

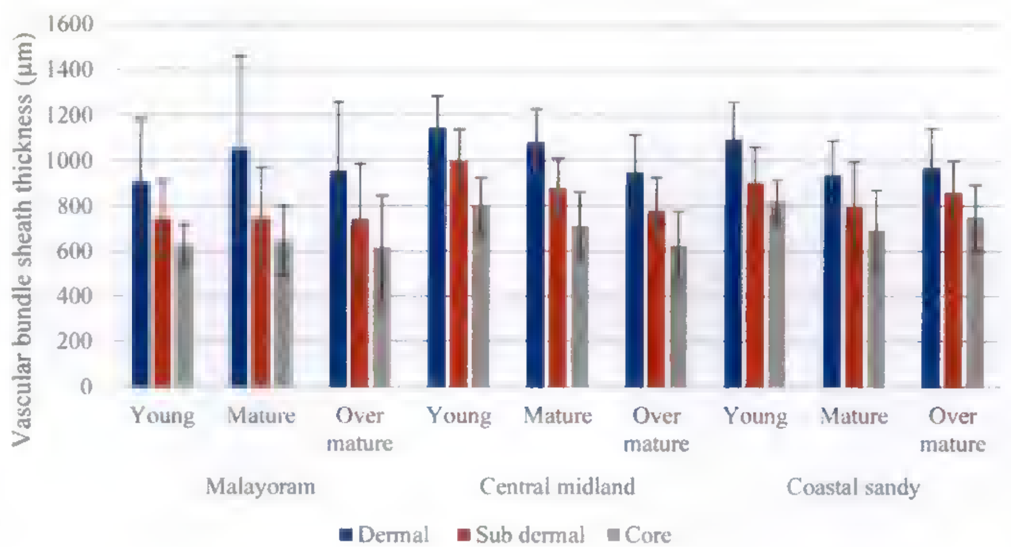

Figure 10. Vascular bundle sheath thickness of coconut palm wood from different agro-climatic zones and age groups

4.2.4. Anatomical properties

The results of anatomical studies (vascular bundle frequency, vascular bundle sheath thickness, vascular bundle diameter, vascular bundle percentage, fibre length, fibre diameter, fibre wall thickness, fibre lumen diameter and vessel diameter) conducted were discussed below.

4.2.4.1. Vascular bundle frequency

Analysis of variance for vascular bundle frequency of coconut palm wood across three agro-climatic zones did not show significant difference even though the values ranged from 19.92 (core wood of young palms) to 71.42 (dermal wood of over mature palms) for Malayoram, 19.70 (core wood of young palms) to 69.74(dermal wood of over mature palms) for Central midland and 13.75 (dermal wood of young palms) to 70.42 (core wood of over mature palms) for Coastal sandy (Figure 9). Following it, there was no significance difference across age groups. As the vascular bundle frequency ranged from 13.75 (core wood) to 52.58 (dermal wood) in young palms, 20.89 (core wood) to 61.25 (core wood) in mature palms and 23.33 (core wood) to 70.42 (dermal wood) in over mature palms. Following it, there was a significant difference across dermal, sub dermal and core wood with regard to vascular bundle in all agro-climatic zones and age groups as in Table 9.

4.2.4.2. Vascular bundle sheath thickness

The vascular bundle sheath thickness ranged from 905.67 μm (dermal wood of young palms) to 1056.08 μm (dermal wood of young palms) for Malayoram, 625.24 μm (core wood of young palms) to 1145.12 μm (core wood of young palms) for Central midland and 750.20 μm (core wood of over mature palms) to 1097.73 μm (dermal wood of young palms) for Coastal sandy. Analysis of variance conducted revealed that there was no significant difference in vascular bundle sheath thickness between agro-climatic zones. However, vascular bundle sheath thickness for young palms ranged from 905.67 μm (dermal wood) to 1145.12 μm (dermal wood), mature palms ranged from 646.74 μm (core wood) to 1083.93 μm (dermal wood) and over mature palm ranged from 613.88 μm (core wood) to

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972.00 µm (dermal wood) (Figure 10). There was no significant difference in vascular bundle sheath thickness across age groups. Contrarily, there was a significant difference in vascular bundle sheath thickness across dermal, sub dermal and core wood in all agro-climatic zones and age groups (Table 10).

4.2.4.3. Vascular bundle diameter

Analysis of variance for vascular bundle diameter of coconut palm wood across three agro-climatic zones did not show significant difference, the values ranged from 962.86 µm (dermal wood of young palms) to 1417.77 µm (core wood of over mature palms) for Malayoram, 886.96 µm (dermal wood of young palms) to 1380.59 µm (core wood of over mature palms) for Central midland and 970.27 µm (dermal wood of over mature palms) to 1323.08 µm (core wood of mature palms) for Coastal sandy (Figure 11). Vascular bundle diameter was also not found to be significantly different across age groups. The vascular bundle diameter ranged from 886.96 µm (dermal wood) to 1205.17 µm (core wood) in young palms, 962.42 µm (dermal wood) to 1323.99 µm (core wood) in mature palms and 987.21 µm (dermal wood) to 1417.77 µm (core wood) in over mature palms. However, there was a significant difference across dermal, sub dermal and core wood in all agro-climatic zones and age groups whose values are tabulated in Table 11.

4.2.4.4. Vascular bundle percentage

The vascular bundle percentage ranged from 20.41 % (core wood of young palms) to 78.16 % (dermal wood of over mature palms) for Malayoram, 20.51 % (core wood of young palms) to 67.99 % (dermal wood of over mature palms) for Central midland and 15.97 % (core wood of mature palms) to 57.51 % (dermal wood of over mature palms) for Coastal sandy. Analysis of variance conducted revealed that there was no significant difference in vascular bundle percentage between agro-climatic zones. Vascular bundle percentage for young palms ranged from 15.97 % (core wood) to 42.96 % (dermal wood), mature palms ranged from 27.33 % (core wood) to 57.21 % (dermal wood) and over mature palm ranged from

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Table 11. Vascular bundle diameter of coconut palm wood from different agro-climatic zones and age groups

Agro-climatic zones	Block	Vascular bundle diameter (µm)								
		Age groups (years)								
		15-25			35-45			55-65		
		Dermal	Sub dermal	Core	Dermal	Sub dermal	Core	Dermal	Sub dermal	Core
Malayoram	1	1075.04	1207.79	1286.13	1089.66	1195.85	1202.44	1321.40	1487.50	1585.47
		(125.99)	(203.40)	(106.00)	(112.46)	(149.66)	(161.67)	(123.95)	(133.55)	(164.96)
	2	896.58	958.74	1074.05	1112.47	1214.50	1325.70	978.55	1496.97	1432.35
		(160.15)	(155.67)	(206.65)	(112.66)	(228.66)	(173.61)	(274.07)	(234.52)	(227.66)
	3	917.26	920.26	926.22	1091.30	1141.63	1150.33	1089.68	1114.57	1398.54
		(116.90)	(142.99)	(160.50)	(158.33)	(137.80)	(191.49	(201.16)	(209.65)	(160.65)
	4	962.55	1121.40	1258.74	1214.75	1488.36	1617.47	1265.87	1147.85	1254.70
		(236.45)	(198.67)	(171.57)	(317.51)	(151.87)	(150.66)	(141.65)	(188.63)	(247.66)
	Mean	962.86	1052.05	1136.28	1127.04	1260.08	1323.99	1163.88	1311.72	1417.77
		(79.70)	(135.57)	(168.77)	(59.39)	(155.29)	(209.02)	(158.19)	(208.92)	(135.77)
Central midland	1	1012.47	1245.70	1378.20	900.51	1039.23	1191.83	1225.00	1355.00	1463.00
		(200.52)	(124.66)	(163.46)	(176.38)	(107.99)	(154.35)	(101.65)	(143.66)	(169.66)
	2	823.47	996.77	1025.47	965.74	1102.47	1254.10	1089.66	1125.47	1275.20
		(197.60)	(163.67)	(151.63)	(222.65)	(169.64)	(238.61)	(234.66)	(127.50)	(176.65)
	3	913.26	974.58	1135.84	865.84	1148.98	1413.61	884.55	1068.71	1189.57
		(159.75)	(123.79)	(234.66)	(164.08)	(153.05)	(129.66)	(266.02)	(171.83)	(135.64)
	4	1011.40	1124.70	1448.58	1025.57	1125.55	1325.70	1150.29	1306.91	1440.53
		(222.15)	(173.62)	(200.97)	(149.60)	(123.65)	(151.67)	(151.88)	(169.69)	(131.11)

Cont.

	5	1089.64	1258.74	1325.47	1025.47	1223.66	1382.47	1233.25	1398.57	1524.58
		(183.66)	(140.65)	(201.62)	(163.66)	(133.65)	(165.15)	(173.67)	(183.62)	(160.61)
	6	796.58	866.80	1124.54	1125.47	1345.60	1387.15	1124.70	1248.70	1285.80
		(114.67)	(116.67)	(126.96)	(157.47)	(153.66)	(123.99)	(112.16)	(221.15)	(200.67)
	7	904.75	912.46	935.24	766.33	847.50	1082.55	985.47	1085.60	1325.47
		(188.96)	(176.64)	(155.66)	(186.65)	(142.36)	(159.61)	(187.64)	(211.65)	(224.66)
	8	832.55	1012.47	1122.50	965.40	1027.85	1125.47	1247.50	1255.40	1445.25
		(161.62)	(149.62)	(174.70)	(163.42)	(147.65)	(185.62)	(167.46)	(201.70)	(147.46)
	9	598.54	765.84	839.77	1021.47	1328.73	1447.91	829.80	1285.57	1475.89
		(160.27)	(209.65)	(161.67)	(242.28)	(166.49)	(156.52)	(236.58)	(122.30)	(133.16)
	Mean	886.96	1017.56	1148.40	962.42	1132.17	1290.09	1085.58	1236.66	1380.59
		(146.49)	(166.26)	(203.55)	(105.87)	(155.86)	(132.53)	(153.73)	(118.02)	(114.02)
Coastal sandy	1	1124.70	1195.80	1224.70	1314.57	1324.76	1624.40	1212.47	1375.80	1454.70
		(116.66)	(175.47)	(163.65)	(127.97)	(231.67)	(143.46)	(186.64)	(192.96)	(221.47)
	2	965.87	1276.21	1285.47	685.47	884.91	945.72	1108.01	1246.48	1251.70
		(147.65)	(181.44)	(143.61)	(216.19)	(166.19)	(117.62)	(238.52)	(220.43)	(111.57)
	3	665.82	885.47	1055.82	1296.33	1213.52	1385.96	965.80	1125.44	1424.70
		(326.85)	(163.46)	(141.47)	(124.37)	(120.59)	(186.67)	(176.54)	(236.50)	(128.65)
	4	1124.70	1145.00	1254.70	1021.14	1214.57	1336.25	662.55	856.84	1053.62
		(111.55)	(110.47)	(220.55)	(128.46)	(163.66)	(143.95)	(89.67)	(96.64)	(200.66)
	Mean	970.27	1125.62	1205.17	1079.38	1159.44	1323.08	987.21	1151.14	1296.18
		(216.34)	(168.97)	(102.61)	(294.92)	(190.32)	(281.26)	(238.89)	(221.24)	(184.81)

Significant between radial positions at 5% level; Value within parentheses is standard deviation (SD)

Table 12. Vascular bundle percentage of coconut palm wood from different agro-climatic zones and age groups

Age group		15-25 years			35-45 years			55-65 years		
Agro-climatic zones	**Block**	**Dermal**	**Sub dermal**	**Core**	**Dermal**	**Sub dermal**	**Core**	**Dermal**	**Sub dermal**	**Core**
Malayoram	1	45.97	40.08	26.40	56.55	43.03	21.94	70.06	66.71	65.78
	2	31.76	22.85	16.60	44.04	37.44	22.53	70.36	39.34	34.89
	3	36.33	23.71	14.59	70.74	46.72	45.36	86.06	51.69	43.23
	4	34.91	31.59	24.05	57.53	53.91	32.86	86.15	42.06	33.37
	Mean	37.24	29.56	20.41	57.21	45.27	30.67	78.16	49.95	44.32
		(6.12)	(8.04)	(5.70)	(10.91)	(6.91)	(11.00)	(9.18)	(12.36)	(14.95)
Central midland	1	47.14	40.23	37.28	50.08	47.58	47.19	73.43	71.10	50.97
	2	35.10	29.81	19.54	30.99	28.94	19.34	78.92	40.09	29.79
	3	29.03	20.88	10.80	40.02	36.27	30.33	74.71	57.53	38.88
	4	43.90	33.49	30.45	44.31	34.48	27.59	63.01	50.50	24.43
	5	46.60	46.02	28.96	39.90	34.87	21.00	68.05	56.30	51.70
	6	21.25	13.90	11.60	55.43	50.05	30.71	62.02	56.60	30.72
	7	31.04	12.88	9.61	26.42	18.61	16.25	58.96	29.30	20.23
	8	31.20	30.04	21.43	30.24	26.26	14.58	83.07	37.17	34.64
	9	18.72	16.40	14.95	42.84	41.99	39.00	49.73	36.21	33.63
	Mean	33.77	27.07	20.51	40.02	35.45	27.33	67.99	48.31	35.00
		(10.41)	(11.82)	(9.85)	(9.53)	(10.10)	(10.84)	(10.59)	(13.42)	(10.76)
Coastal sandy	1	43.69	41.53	22.76	68.73	44.19	37.66	68.47	65.38	44.85
	2	51.99	32.71	19.03	28.77	27.46	20.13	62.64	52.45	36.08
	3	17.23	15.43	9.33	94.10	50.09	43.23	61.75	41.76	22.84
	4	58.92	21.61	12.77	36.83	40.92	20.09	37.18	27.28	25.16
	Mean	42.96	27.82	15.97	57.11	40.66	30.27	57.51	46.72	32.23
		(18.24)	(11.61)	(6.05)	(30.10)	(9.59)	(11.96)	(13.88)	(16.16)	(10.20)

Significant between age groups and radial positions at 5% level; Value within parentheses is standard deviation (SD)

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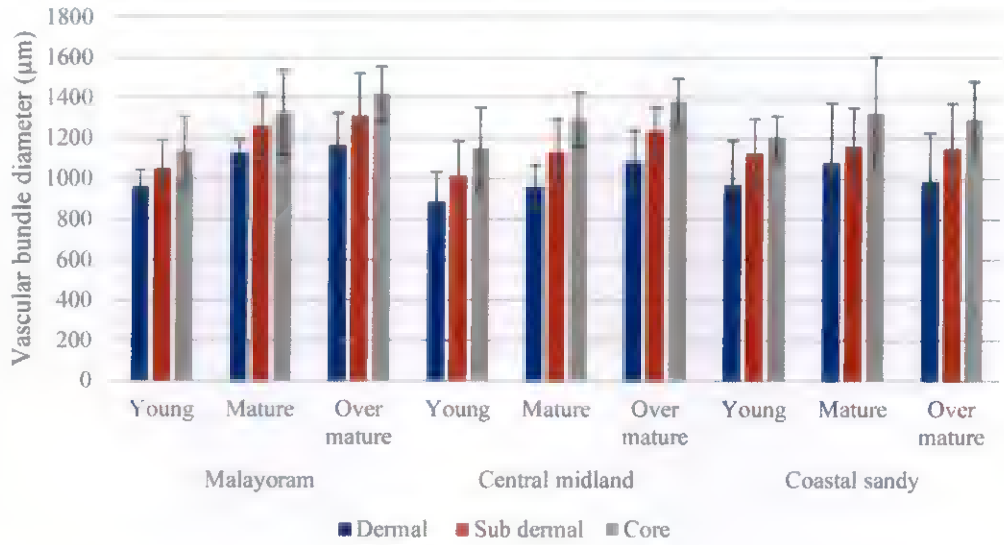

Figure 11. Vascular bundle diameter of coconut palm wood from different agro-climatic zones and age groups

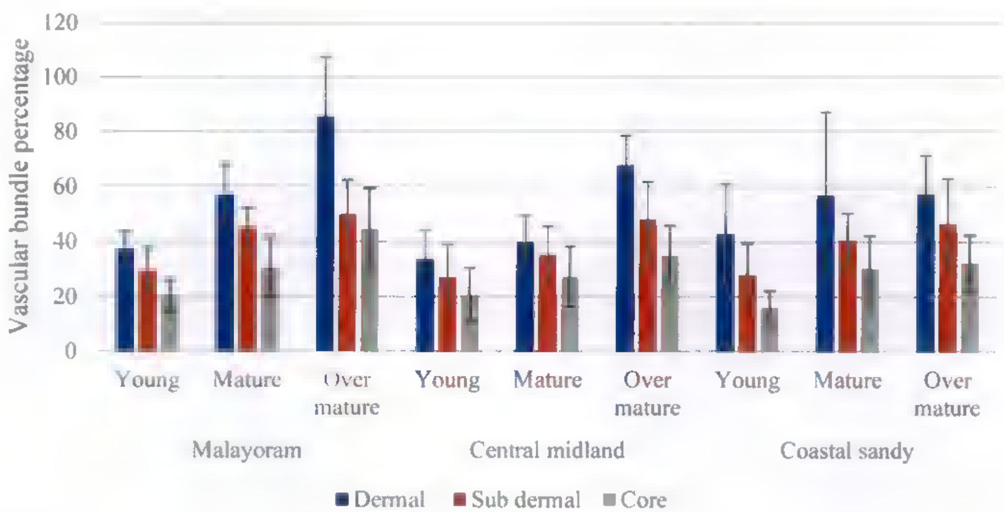

Figure 12. Vascular bundle percentage of coconut palms from different zones and age groups

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32.23 % (core wood) to 78.16 % (dermal wood) (Figure 12). There was a significant difference in vascular bundle percentage across age groups. Similarly, there was significant difference across dermal, sub dermal and core wood in all agro-climatic zones and age groups (Table 12).

4.2.4.5. Fibre length

Analysis of variance for fibre length of coconut palm wood across three agro-climatic zones did not show significant difference, the values ranged from 1949.60 μm (dermal wood of over mature palms) to 2591.34 μm (core wood of mature palms) for Malayoram, 1902.15 μm (dermal wood of over mature palms) to 2461.22 μm (core wood of young palms) for Central midland and 1687.36 μm (dermal wood of over mature palms) to 2812.93 μm (core wood of young palms) for Coastal sandy (Figure 13). Likewise, the fibre length was also found to be not significantly different across age groups. The fibre length ranged from 1911.77 μm (dermal wood) to 2812.93 μm (core wood) in young palms, 1911.70 μm (dermal wood) to 2672.23 μm (core wood) in mature palms and 1687.36 μm (dermal wood) to 2478.55 μm (core wood) in over mature palms. There was significant difference across dermal, sub dermal and core wood in all agro-climatic zones and age groups whose values are tabulated in Table 13.

4.2.4.6. Fibre diameter

Analysis of variance for fibre diameter of coconut palm wood across three agro-climatic zones does not show significant difference, the values ranged from 32.26 μm (core wood of young palms) to 50.10 μm (dermal wood of over mature palms) for Malayoram, 32.80 μm (core wood of young palms) to 48.96 μm (dermal wood of over mature palms) for Central midland and 37.71 μm (core wood of young palms) to 53.84 μm (dermal wood of over mature palms) for Coastal sandy (Figure 14). Likewise, the fibre diameter was also not significantly different across different age groups. The fibre diameter ranged from 32.26 μm (core wood) to 39.98 μm (sub dermal wood) in young palms, 33.60 μm (core wood) to 46.85 μm (dermal wood) in mature palms and 34.86 μm (core wood) to 53.84 μm (core wood)

Table 13. Fibre length of coconut palm wood from different agro-climatic zones and age groups

Agro-climatic zones	Block	Fibre length (μm)								
		Age groups (years)								
		15-25			35-45			55-65		
		Dermal	Sub dermal	Core	Dermal	Sub dermal	Core	Dermal	Sub dermal	Core
Malayoram	1	2125.70 (550.67)	2221.40 (442.13)	2358.00 (236.85)	2012.40 (667.67)	2049.66 (455.32)	2458.00 (321.88)	1954.70 (201.46)	1985.40 (225.95)	2224.00 (455.96)
	2	1896.50 (225.65)	2145.70 (354.95)	2865.90 (412.66)	2021.74 (403.57)	2155.80 (203.50)	2756.90 (551.57)	1856.90 (324.55)	1985.40 (552.85)	2558.20 (600.96)
	3	2232.50 (124.31)	2434.50 (409.95)	3022.40 (736.38)	2224.57 (598.62)	2358.00 (547.15)	2895.45 (465.12)	2021.40 (532.16)	2125.00 (426.15)	2584.00 (345.84)
	4	2223.00 (365.80)	2254.40 (478.26)	2458.70 (345.15)	1998.00 (299.65)	2021.40 (456.49)	2255.00 (223.55)	1965.40 (475.16)	2214.54 (568.42)	2548.00 (223.55)
	Mean	2119.43 (156.26)	2264.00 (122.44)	2676.25 (318.54)	2064.18 (107.37)	2146.22 (152.59)	2591.34 (289.14)	1949.60 (68.37)	2077.59 (112.545	2478.55 (170.38)
Central midland	1	2125.40 (215.57)	2325.40 (426.65)	2558.40 (526.95)	2067.31 (443.66)	2237.40 (393.43)	2425.70 (538.42)	1927.73 (221.44)	2327.75 (722.68)	2570.59 (753.26)
	2	1898.50 (236.67)	2355.57 (496.54)	2658.40 (354.44)	1758.50 (224.84)	2235.40 (358.57)	2452.80 (423.22)	1350.59 (407.42)	1960.71 (841.86)	2254.70 (582.44)
	3	2247.00 (235.55)	2458.00 (436.46)	2458.71 (548.57)	2154.00 (472.56)	2314.57 (652.22)	2321.40 (325.54)	1985.70 (274.52)	2012.40 (689.13)	2214.57 (325.65)
	4	2254.70 (563.76)	2301.47 (426.85)	2321.00 (454.75)	2014.80 (412.26)	2127.45 (542.26)	2224.00 (234.65)	1965.47 (234.61)	2012.40 (425.66)	2032.50 (335.62)

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Cont.

	5	2301.24 (441.36)	2354.70 (367.17)	2654.70 (539.16)	2135.40 (472.65)	2221.00 (321.52)	2465.80 (229.62)	1999.65 (556.52)	2124.40 (254.66)	2365.80 (368.66)
	6	2358.90 (478.52)	2365.80 (569.67)	2458.00 (412.62)	2214.57 (246.17)	2254.80 (295.65)	2396.58 (389.60)	2125.80 (458.66)	2198.70 (384.42)	2365.80 (200.66)
	7	1987.26 (762.73)	2232.63 (546.57)	2291.48 (900.94)	2191.17 (595.05)	2198.04 (723.11)	2218.97 (111.57)	1985.20 (354.15)	2024.70 (338.62)	2125.40 (624.66)
	8	2014.50 (432.15)	2225.40 (325.66)	2427.80 (458.56)	2011.20 (418.56)	2132.54 (532.17)	2214.55 (275.65)	1914.20 (256.66)	1983.24 (431.22)	2039.87 (325.52)
	9	1997.00 (245.16)	2124.70 (352.52)	2322.50 (532.17)	1992.00 (412.66)	2031.44 (532.15)	2055.80 (472.12)	1865.00 (235.62)	1912.47 (345.62)	1985.40 (248.17)
	Mean	2131.61 (164.30)	2304.85 (97.88)	2461.22 (139.02)	2059.88 (139.47)	2194.74 (84.56)	2308.40 (139.22)	1902.15 (219.04)	2061.86 (131.50)	2217.18 (193.06)
Coastal sandy	1	2021.40 (542.56)	2358.74 (412.65)	2785.90 (322.65)	1985.40 (368.66)	2214.50 (351.54)	2423.50 (236.52)	1758.40 (245.56)	2112.45 (224.52)	2254.70 (521.85)
	2	1658.50 (423.66)	2625.80 (325.62)	2845.70 (386.66)	1801.67 (228.65)	2524.10 (125.60)	2756.00 (325.46)	1198.97 (298.54)	1584.82 (659.82)	2654.30 (566.37)
	3	1958.80 (556.64)	2016.43 (453.85)	2598.74 (782.81)	1951.15 (433.45)	2454.58 (733.69)	2547.31 (411.76)	1923.57 (233.44)	2235.50 (436.46)	2325.68 (399.46)
	4	2012.40 (176.66)	2124.20 (267.66)	3021.40 (325.46)	1908.60 (938.76)	1944.80 (238.95)	2962.10 (438.66)	1868.50 (245.66)	1884.57 (229.66)	2547.80 (124.46)
	Mean	1912.78 (171.75)	2281.29 (270.50)	2812.94 (174.30)	1911.70 (79.80)	2284.50 (262.45)	2672.23 (237.00)	1687.36 (332.76)	1954.33 (286.04)	2445.62 (186.93)

Significant between radial positions at 5% level; Value within parentheses is standard deviation (SD)

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Table 14. Fibre diameter of coconut palm wood from different agro-climatic zones and age groups

Agro-climatic zones	Block	Fibre diameter (µm)								
		Age groups (years)								
		15-25			35-45			55-65		
		Dermal	Sub dermal	Core	Dermal	Sub dermal	Core	Dermal	Sub dermal	Core
Malayoram	1	34.97 (7.47)	34.12 (6.62)	30.04 (8.70)	37.89 (10.94)	35.10 (11.59)	34.53 (5.70)	44.85 (11.66)	36.47 (10.62)	34.45 (8.26)
	2	36.58 (11.66)	34.37 (7.69)	33.25 (10.66)	37.58 (6.62)	35.99 (5.99)	33.81 (4.27)	63.69 (11.56)	38.34 (10.63)	35.88 (5.97)
	3	35.24 (5.51)	33.33 (1.55)	32.64 (1.94)	47.57 (10.97)	36.25 (7.63)	33.48 (9.27)	42.87 (11.07)	38.66 (10.62)	35.15 (9.69)
	4	47.93 (4.63)	34.10 (7.66)	33.12 (11.20)	53.33 (6.56)	37.15 (7.45)	32.58 (8.55)	49.01 (9.59)	41.25 (8.22)	33.96 (7.64)
	Mean	38.68 (6.21)	33.98 (0.45)	32.26 (1.50)	44.09 (7.71)	36.12 (0.84)	33.60 (0.81)	50.11 (9.41)	38.68 (1.97)	34.86 (0.84)
Central midland	1	29.70 (10.14)	28.80 (7.60)	28.14 (5.70)	34.15 (11.27)	33.69 (5.53)	33.21 (4.90)	45.44 (10.61)	40.11 (6.93	37.27 (8.73)
	2	34.25 (7.70)	33.69 (5.70)	33.42 (8.70)	37.54 (11.70)	36.02 (4.67)	35.95 (6.97)	44.46 (10.45)	41.83 (5.75)	38.40 (4.72)
	3	34.50 (10.27)	35.47 (5.69)	33.12 (4.95)	42.79 (6.69)	38.47 (11.97)	36.66 (10.99)	51.32 (9.69)	41.59 (7.27)	35.14 (5.64)
	4	47.55 (10.95)	35.56 (6.49)	34.22 (11.55)	54.36 (12.70)	40.37 (10.97)	34.75 (4.91)	49.47 (3.15)	43.70 (5.10)	33.70 (7.96)

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Cont.

	5	49.69	41.92	33.65	41.77	39.82	34.99	45.73	40.66	37.54
		(6.80)	(5.20)	(10.70)	(9.16)	(9.48)	(8.95)	(7.94)	(5.95	(10.96)
	6	34.33	31.79	31.44	47.55	36.30	31.86	50.59	38.21	35.21
		(5.26)	(2.61)	(10.66)	(5.90)	(5.16)	(4.50)	(7.70)	(6.06)	(10.70)
	7	32.19	31.04	31.00	43.31	42.56	40.05	44.83	43.39	41.50
		(3.22)	(2.83)	(5.68)	(7.07)	(10.46)	(11.27)	(5.63)	(4.65)	(11.26)
	8	37.26	34.98	34.01	53.76	44.66	31.59	58.12	50.26	41.97
		(7.70)	(8.65)	(8.17)	(2.80)	(10.70)	(5.66)	(4.50)	(7.267	(9.70)
	9	40.25	38.99	36.23	47.24	42.93	39.02	50.68	47.16	34.87
		(10.66)	(9.66)	(12.22)	(2.20)	(11.95)	(8.70)	(10.96)	(3.69)	(4.95)
	Mean	37.75	34.69	32.81	44.72	39.42	35.34	48.96	42.99	37.29
		(6.85)	(4.03)	(2.33)	(6.77)	(3.63)	(2.94)	(4.41)	(3.72)	(2.93)
Coastal sandy	1	41.44	40.64	37.66	48.47	48.11	41.58	56.71	54.38	34.35
		(10.95)	(8.27)	(11.66)	(5.27)	(6.07)	(7.70)	(6.27)	(10.27)	(5.95)
	2	29.58	35.24	36.46	38.50	37.47	37.30	49.43	39.49	38.62
		(4.75)	(5.50)	(6.95)	(6.16)	(6.33)	(9.05)	(11.43)	(7.73)	(6.42)
	3	43.88	41.78	40.47	50.68	48.57	43.45	55.66	53.96	39.58
		(6.65)	(7.65)	(5.34)	(10.37)	(8.44)	(10.12)	(4.65)	(7.93)	(10.70)
	4	43.84	42.26	36.24	49.73	48.33	47.55	53.57	51.15	41.58
		(10.12)	(9.14)	(5.14)	(4.84)	(7.11)	(6.16)	(8.32)	(8.95)	(7.95)
	Mean	39.68	39.98	37.71	46.85	45.62	42.47	53.84	49.74	38.53
		(6.83)	(3.23)	(1.94)	(5.64)	(5.44)	(4.25)	(3.22)	(6.99)	(3.05)

Significant between radial positions at 5% level; Value within parentheses is standard deviation (SD)

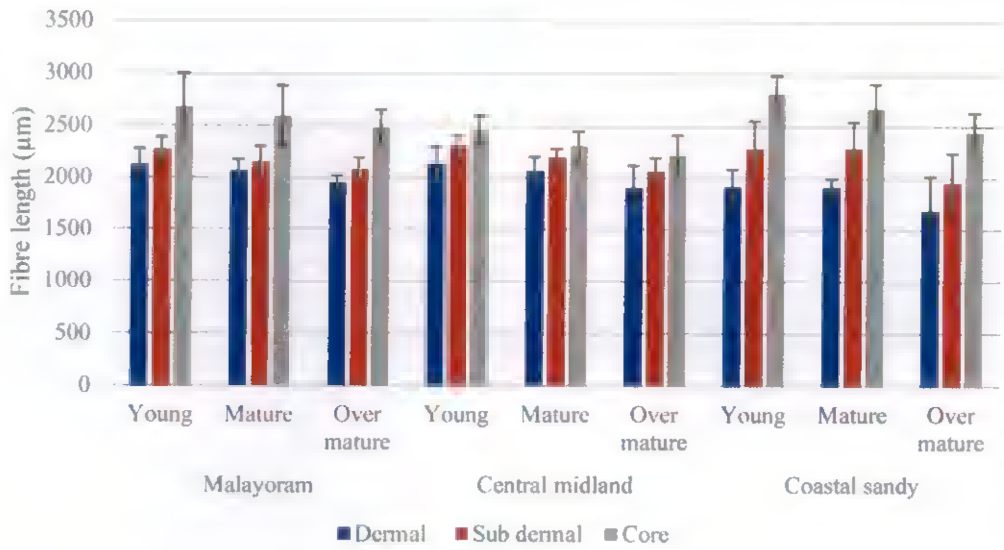

Figure 13. Fibre length of coconut palm wood from different agro-climatic zones and age groups

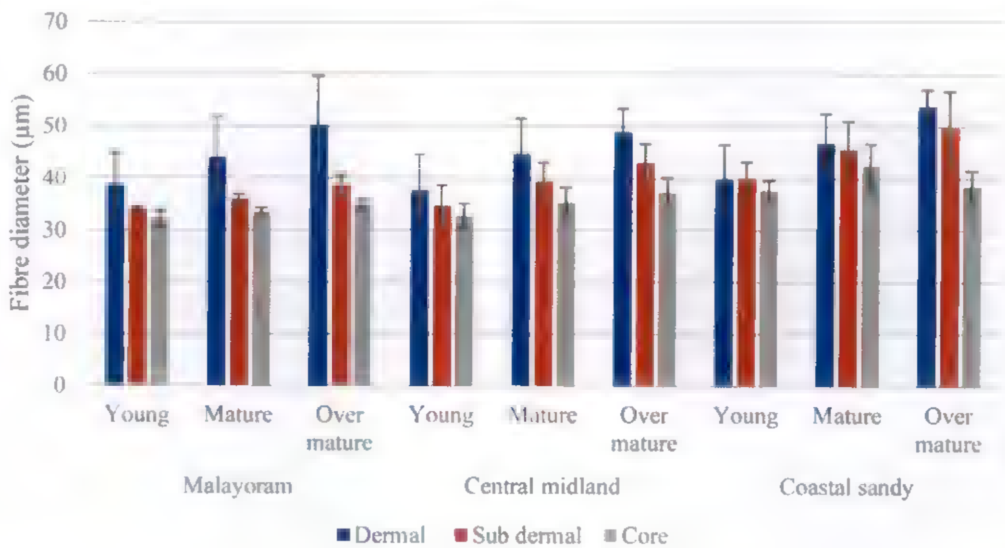

Figure 14. Fibre diameter of coconut palm wood from different agro-climatic zones and age groups

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in over mature palms. There was a significant difference across dermal, sub dermal and core wood in all agro-climatic zones and age groups whose values are tabulated in Table 14.

4.2.4.7. Fibre lumen diameter

The fibre lumen diameter value ranged from 8.15 µm (dermal wood of over mature palms) to 20.49 µm (core wood of young palms) for Malayoram, 6.48 µm (dermal wood of over mature palms) to 20.71 µm (core wood of young palms) for Central midland and 5.70 µm (dermal wood of over mature palms) to 21.89 µm (core wood of young palms) for Coastal sandy (Figure 15). Analysis of variance conducted revealed that there was no significant difference in fibre lumen diameter between agro-climatic zones. Thereupon fibre lumen diameter for young palms ranged from 13.15 µm (dermal wood) to 21.89 µm (core wood), mature palms ranged from 10.55 µm (dermal wood) to 18.75 µm (core wood) and over mature palm ranged from 5.70 µm (dermal wood) to 13.65 µm (core wood). There was a significant difference in fibre lumen diameter across age groups and there was a significant difference in fibre lumen diameter across dermal, sub dermal and core wood in all agro-climatic zones and age groups (Table 15).

4.2.4.8. Fibre wall thickness

Analysis of variance for fibre wall thickness of coconut palm wood across three agro-climatic zones did not show significant difference, the values ranged from 7.42 µm (core wood of mature palms) to 20.98 µm (dermal wood of over mature palms) for Malayoram, 6.04 µm (core wood of young palms) to 21.24 µm (dermal wood of over mature palms) for Central midland and 7.91 µm (core wood of young palms) to 24.07 µm (dermal wood of over mature palms) for Coastal sandy. However, the fibre wall thickness was also found to be significantly different across age groups. The fibre wall thickness ranged from 5.89 µm (core wood) to 13.267 µm (dermal wood) in young palms, 7.42 µm (core wood) to 18.15 µm (dermal wood) in mature palms and 10.60 µm (core wood) to 24.07 µm (dermal wood) in over mature palms (Figure 16). Similarly, there was a significant

Table 15. Fibre lumen diameter of coconut palm wood from different agro-climatic zones and age groups

Agro-climatic zones	Block	Fibre lumen diameter (µm)								
		Age groups (years)								
		15-25			35-45			55-65		
		Dermal	Sub dermal	Core	Dermal	Sub dermal	Core	Dermal	Sub dermal	Core
Malayoram	1	18.79	19.41	19.85	11.47	14.40	16.45	7.69	10.57	13.47
		(1.56)	(1.72)	(3.65)	(0.85)	(0.99)	(1.33)	(1.545	(0.46)	(0.96)
	2	15.14	17.47	20.47	10.86	14.88	17.14	12.50	13.47	14.88
		(2.45)	(2.05)	(3.05)	(1.85)	(0.66)	(1.26)	(0.55)	(0.79)	(2.55)
	3	14.93	20.10	21.48	18.47	20.80	20.95	4.85	12.48	12.50
		(2.61)	(1.52)	(1.30)	(2.65)	(2.16)	(2.55)	(0.79)	(2.59)	(1.30)
	4	18.92	19.25	20.14	13.75	15.14	20.47	7.55	10.85	13.75
		(0.66)	(2.49)	(1.77)	(0.79)	(1.30)	(1.30)	(0.63)	(1.18)	(1.95)
	Mean	16.89	19.06	20.49	13.63	16.31	18.75	8.15	11.84	13.65
		(2.15)	(1.12)	(0.71)	(3.46)	(3.01)	(2.29)	(3.18)	(1.38)	(0.98)
Central midland	1	12.95	15.48	17.98	10.55	15.59	18.43	8.75	12.63	13.97
		(3.45)	(1.55)	(0.45)	(2.30)	(5.15)	(3.97)	(1.16)	(0.71)	(6.79)
	2	15.74	18.33	22.50	12.58	13.74	18.84	7.52	8.70	14.80
		(2.47)	(0.75)	(0.86)	(1.45)	(0.33)	(0.45)	(1.08)	(0.65)	(3.54)
	3	13.54	18.54	22.54	11.26	16.47	21.54	5.66	11.58	13.56
		(0.72)	(0.63)	(0.48)	(1.00)	(0.55)	(0.27)	(1.25)	(0.56)	(2.65)
	4	19.45	21.25	24.66	16.45	17.15	19.47	6.25	9.75	12.58
		(0.27)	(0.62)	(1.27)	(1.75)	(0.97)	(0.49)	(1.49)	(2.26)	(1.30)

Cont.

	5	18.55 (1.85)	19.58 (1.97)	22.75 (1.40)	11.58 (1.63)	14.85 (1.33)	17.46 (0.79)	4.68 (0.42)	10.25 (0.85)	13.57 (2.95)
	6	10.96 (1.46)	17.14 (1.27)	18.48 (2.46)	7.45 (0.46)	14.85 (1.27)	15.12 (1.27)	5.46 (1.30)	8.24 (0.65)	8.58 (0.79)
	7	12.86 (0.94)	14.66 (0.65)	14.86 (3.00)	10.83 (0.63)	11.20 (1.36)	13.75 (0.93)	4.12 (2.05)	4.65 (0.43)	6.24 (1.99)
	8	11.84 (0.76)	12.19 (0.19)	17.54 (0.80)	6.25 (0.26)	11.54 (0.37)	21.59 (1.76)	5.59 (1.30)	7.66 (0.33)	8.47 (0.76)
	9	16.45 (0.46)	20.47 (0.84)	25.12 (0.54)	10.77 (0.43)	16.25 (1.46)	21.58 (2.03)	10.24 (2.01)	14.59 (0.47)	15.14 (0.95)
	Mean	14.71 (2.99)	17.52 (2.95)	20.71 (3.58)	10.86 (2.91)	14.63 (2.11)	18.64 (2.83)	6.48 (1.99)	9.78 (2.94)	11.88 (3.24)
Coastal sandy	1	11.47 (1.85)	14.86 (0.96)	20.47 (1.49)	10.47 (0.95)	13.64 (1.46)	20.99 (1.77)	5.97 (1.29)	7.47 (1.30)	17.55 (2.17)
	2	7.47 (2.15)	13.14 (1.45)	25.12 (1.26)	9.85 (1.54)	12.47 (1.41)	16.76 (0.21)	1.00 (0.64)	5.75 (0.85)	8.80 (3.85)
	3	15.40 (3.67)	17.68 (2.57)	16.53 (3.32)	8.43 (0.48)	9.26 (1.40)	10.85 (0.92)	5.63 (0.49)	6.88 (0.42)	7.99 (0.96)
	4	18.24 (4.96)	23.65 (5.96)	25.44 (2.79)	13.44 (0.70)	16.41 (2.16)	22.85 (2.48)	5.57 (0.66)	6.24 (1.96)	17.15 (1.46)
	Mean	13.15 (4.69)	17.33 (4.61)	21.89 (4.23)	10.55 (2.11)	12.95 (2.96)	17.86 (5.32)	5.70 (0.18)	6.59 (0.75)	12.87 (5.18)

Significant in age groups and between radial positions at 5% level; Value within parentheses is standard deviation (SD)

Table 16. Fibre wall thickness of coconut palm wood from different agro-climatic zones and age groups

Agro-climatic zones	Block	Fibre wall thickness (μm)								
		Age groups (years)								
		15-25			35-45			55-65		
		Dermal	Sub dermal	Core	Dermal	Sub dermal	Core	Dermal	Sub dermal	Core
Malayoram	1	8.20	7.36	5.10	13.21	10.35	9.04	18.58	12.95	10.49
		(1.65)	(0.33)	(0.76)	(1.63)	(1.65)	(0.32)	(1.52)	(0.96)	(0.33)
	2	10.72	8.45	6.39	13.37	10.56	8.34	25.60	12.44	10.50
		(0.45)	(0.46)	(1.27)	(0.96)	(1.30)	(0.47)	(2.66)	(1.65)	(1.63)
	3	10.15	6.62	5.58	14.55	7.73	6.27	19.01	13.09	11.32
		(0.76)	(0.97)	(1.47)	(0.48)	(0.55)	(0.63)	(1.30)	(1.65)	(0.96)
	4	14.50	7.43	6.49	19.79	11.00	6.06	20.73	15.21	10.11
		(1.27)	(1.27)	(1.0)	(1.62)	(0.76)	(0.50)	(2.50)	(2.30)	(0.84)
	Mean	10.90	7.46	5.89	15.23	9.91	7.42	20.98	13.42	10.61
		(2.64)	(0.75)	(0.67)	(3.10)	(1.48)	(1.49)	(3.22)	(1.22)	(0.51)
Central midland	1	8.38	6.66	5.08	11.80	9.05	7.39	18.35	13.74	11.65
		(0.94)	(0.65)	(0.96)	(1.27)	(1.95)	(1.25)	(2.49)	(0.96)	(0.16)
	2	9.25	7.68	5.46	12.48	11.14	8.55	18.47	16.56	11.80
		(0.33)	(0.76)	(0.16)	(3.06)	(0.95)	(0.63)	(1.26)	(3.56)	(0.27)
	3	10.48	8.47	5.29	15.77	11.00	7.56	22.83	15.00	10.79
		(0.16)	(1.96)	(0.23)	(2.96)	(0.49)	(0.47)	(1.30)	(1.29)	(0.76)
	4	14.05	7.16	4.78	18.96	11.61	7.64	21.61	16.97	10.56
		(0.66)	(0.13)	(0.42)	(0.42)	(1.63)	(1.95)	(2.97)	(1.40)	(1.27)

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Cont.

	5	15.57 (1.96)	11.17 (2.16)	5.45 (1.19)	15.10 (1.75)	12.48 (1.95)	8.77 (1.62)	20.52 (1.85)	15.21 (1.18)	11.99 (2.18)
	6	11.68 (0.93)	7.32 (0.32)	6.48 (1.55)	20.05 (2.62)	10.72 (1.65)	8.37 (0.57)	22.57 (0.46)	14.98 (0.85)	13.32 (1.26)
	7	9.67 (0.18)	8.19 (1.70)	8.07 (2.26)	16.24 (1.97)	15.68 (2.30)	13.15 (1.25)	20.35 (2.47)	19.37 (0.70)	17.63 (2.50)
	8	12.71 (0.78)	11.39 (1.66)	8.23 (1.22)	23.75 (0.96)	16.56 (1.50)	5.00 (0.56)	26.27 (1.50)	21.30 (1.56)	16.75 (1.29)
	9	11.90 (1.66)	9.26 (0.63)	5.56 (0.86)	18.24 (0.95)	13.34 (2.30)	8.72 (0.65)	20.22 (0.62)	16.29 (2.27)	9.87 (1.30)
	Mean	11.52 (2.34)	8.59 (1.71)	6.05 (1.28)	16.93 (3.77)	12.40 (2.43)	8.35 (2.14)	21.24 (2.45)	16.60 (2.38)	12.71 (2.73)
Coastal sandy	1	14.98 (1.96)	12.90 (0.79)	8.60 (0.85)	19.00 (1.43)	17.24 (0.66)	10.30 (0.72)	25.37 (3.27)	23.45 (1.48)	8.40 (0.89)
	2	11.06 (1.63)	11.05 (0.46)	5.67 (0.40)	14.33 (3.07)	12.50 (0.43)	10.27 (0.33)	21.90 (3.00)	16.87 (0.80)	0.87 (0.75)
	3	14.24 (1.50)	12.05 (0.65)	11.97 (1.67)	21.13 (3.66)	19.66 (0.66)	16.30 (2.19)	25.02 (2.25)	23.54 (0.45)	15.80 (1.49)
	4	12.80 (0.46)	9.31 (0.27)	5.40 (1.24)	18.15 (1.24)	15.96 (1.93)	12.35 (1.90)	24.00 (1.26)	22.45 (0.96)	12.22 (0.30)
	Mean	13.27 (1.73)	11.32 (1.54)	7.91 (3.07)	18.15 (2.84)	16.34 (2.98)	12.30 (2.84)	24.07 (1.56)	21.58 (3.18)	12.83 (3.32)

Significant in age groups and between radial positions at 5% level; Value within parentheses is standard deviation (SD)

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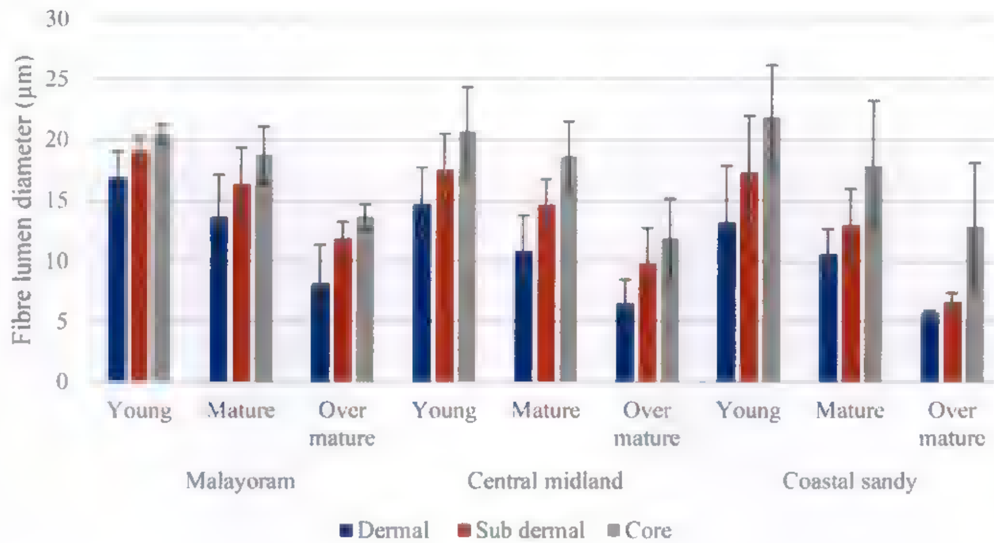

Figure 15. Fibre lumen diameter of coconut palm wood from different agro-climatic zones and age groups

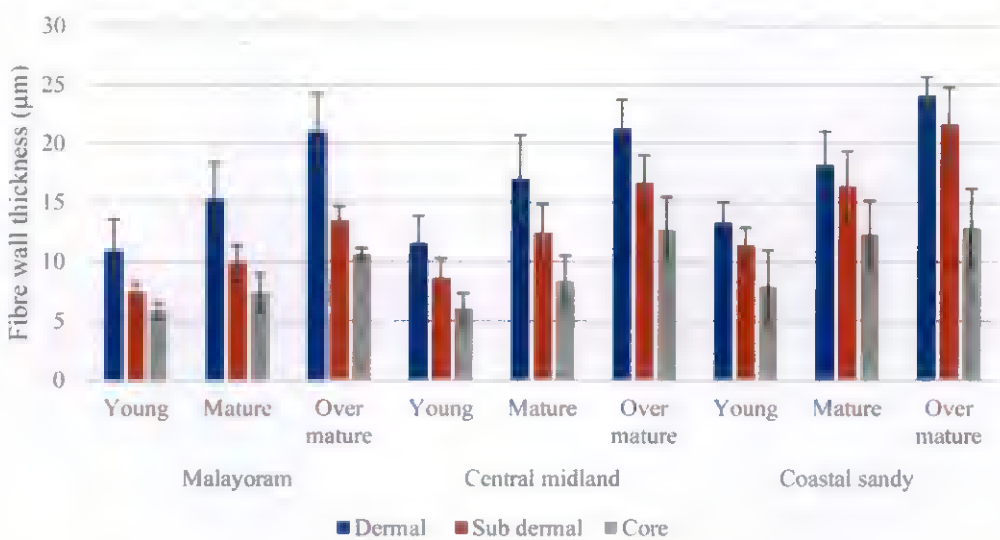

Figure 16. Fibre wall thickness of coconut palm wood from different agro-climatic zones and age groups

difference across dermal, sub dermal and core wood in all agro-climatic zones and age groups whose values are tabulated in Table 16.

4.2.4.9. Vessel diameter

The vessel diameter did not exhibit significant difference across three agro-climatic zones. However, the values ranged from 196.31 μm (dermal wood of over mature palms) to 254.47 μm (core wood of young palms) for Malayoram, 161.70 μm (dermal wood of over mature palms) to 227.39 μm (core wood of young palms) for Central midland and 167.09 μm (dermal wood of over mature palms) to 237.17 μm (core wood of young palms) for Coastal sandy (Figure 17). The vessel lumen diameter also found to be significantly different across age groups. The vessel lumen diameter ranged from 183.19 μm (dermal wood) to 254.47 μm (core wood) in young palms, 182.35 μm (dermal wood) to 237.72 μm (core wood) in mature palms and 161.70 μm (dermal wood) to 229.92 μm (young wood) in over mature palms. There was a significant difference across dermal, sub dermal and core wood in all agro-climatic zones and age groups whose values are tabulated in Table 17.

4.2.5. Mechanical properties

Coconut palm wood with density above 650 kg m^{-3} was selected. The selected samples include dermal wood of 26 (10 mature + 16 over mature) coconut palms from the three agro-climatic zones. The result of mechanical properties of palm wood studied.

4.2.5.1. Static bending test

4.2.5.1.1. Modulus of rupture

Modulus of rupture (MOR) of the coconut palm wood is shown in Table 18 and 19. MOR ranges from 655.24 kg cm^{-2} (Malayoram) to 910.29 kg cm^{-2} (Coastal sandy) for mature palms. For over mature palms MOR ranges from 880.84 kg cm^{-2} (Central midland) to 1079.73 kg cm^{-2} (Malayoram) (Figure 18).

Table 17. Vessel lumen diameter of coconut palm wood from different agro-climatic zones and age groups

Agro-climatic zones	Block	Vessel lumen diameter (µm)								
		Age groups (years)								
		15-25			35-45			55-65		
		Dermal	Sub dermal	Core	Dermal	Sub dermal	Core	Dermal	Sub dermal	Core
Malayoram	1	214.57 (40.33)	236.58 (20.65)	254.78 (50.65)	185.47 (54.56)	196.58 (42.56)	214.57 (49.61)	178.55 (65.62)	179.85 (41.95)	185.25 (47.16)
	2	243.55 (60.99)	265.40 (45.95)	295.80 (63.37)	235.47 (41.17)	245.88 (52.61)	265.89 (57.61)	168.54 (65.29)	185.06 (53.14)	239.42 (35.56)
	3	172.81 (44.72)	180.67 (41.99)	198.75 (45.22)	194.66 (21.71)	210.08 (65.27)	234.63 (78.09)	223.58 (29.0)	251.47 (27.65)	265.47 (65.83)
	4	245.88 (46.16)	259.87 (21.96)	268.55 (73.61)	190.31 (77.18)	226.33 (55.35)	235.80 (39.46)	214.58 (43.14)	223.58 (56.46)	229.56 (57.65)
	Mean	219.20 (34.05)	235.63 (38.71)	254.47 (40.87)	201.48 (22.97)	219.72 (21.26)	237.72 (21.15)	196.31 (26.86)	209.99 (33.84)	229.92 (33.42)
Central midland	1	214.57 (64.67)	225.47 (28.17)	226.58 (27.65)	201.46 (43.95)	235.46 (55.65)	247.85 (28.65)	204.58 (42.55)	225.47 (53.16)	248.97 (65.42)
	2	201.47 (67.15)	212.55 (47.13)	224.58 (68.67)	217.85 (22.50)	225.47 (37.96)	229.56 (41.72)	180.21 (23.66)	185.48 (44.63)	186.58 (42.84)
	3	198.57 (22.31)	201.40 (42.18)	225.47 (44.12)	161.38 (47.79)	169.46 (53.18)	182.47 (22.96)	149.97 (29.15)	251.34 (34.89)	284.76 (61.24)

Cont.

	4	215.78	236.56	265.84	224.78	245.87	254.47	121.69	149.13	221.24
		(21.73)	(45.33)	(55.67)	(59.63)	(49.66)	(57.57)	(39.70)	(75.07)	(75.67)
	5	178.94	195.88	201.48	172.55	189.68	201.45	158.55	167.46	171.24
		(22.66)	(28.67)	(39.66)	(22.67)	(42.47)	(47.65)	(22.96)	(31.55)	(20.65)
	6	184.77	192.21	201.45	179.85	182.36	191.26	165.88	176.58	179.87
		(22.67)	(47.67)	(46.65)	(27.65)	(55.15)	(65.15)	(41.85)	(38.52)	(30.76)
	7	215.47	236.58	247.58	201.47	215.48	226.88	184.75	194.75	198.57
		(29.66)	(47.61)	(41.51)	(53.67)	(47.65)	(65.66)	(22.67)	(39.67)	(60.55)
	8	224.55	236.57	254.78	219.88	236.88	268.45	176.59	198.54	247.75
		(24.57)	(42.63)	(53.65)	(22.66)	(47.67)	(49.66)	(65.61)	(52.17)	(50.66)
	9	131.03	168.55	198.75	193.78	224.51	236.58	113.09	191.08	235.84
		(47.49)	(25.64)	(47.47)	(66.23)	(24.19)	(46.17)	(40.88)	(52.41)	(66.66)
	Mean	196.13	211.75	227.39	197.00	213.91	226.55	161.70	193.31	219.43
		(28.73)	(24.09)	(24.53)	(22.20)	(26.97)	(29.41)	(29.71)	(30.41)	(38.10)
Coastal sandy	1	215.47	235.65	245.76	192.57	223.54	232.55	190.32	214.55	219.87
		(22.56)	(26.62)	(47.61)	(53.62)	(42.67)	(22.95)	(36.65)	(45.66)	(21.66)
	2	132.55	164.47	198.58	148.43	164.94	195.87	155.20	168.79	192.12
		(53.52)	(47.69)	(41.66)	(65.47)	(50.37)	(33.67)	(44.73)	(62.26)	(32.62)
	3	192.32	223.58	258.47	162.58	192.59	241.65	186.66	195.49	214.40
		(31.14)	(34.66)	(29.22)	(33.36)	(46.60)	(37.66)	(46.93)	(57.62)	(39.67)
	4	192.44	225.70	245.87	225.84	235.45	254.78	136.20	165.28	185.47
		(44.67)	(43.66)	(50.66)	(41.65)	(47.65)	(20.57)	(26.87)	(24.66)	(60.42)
	Mean	183.19	212.35	237.17	182.35	204.13	231.21	167.10	186.03	202.97
		(35.48)	(32.35)	(26.41)	(34.34)	(31.76)	(25.27)	(25.94)	(23.32)	(16.74)

Significant between radial positions at 5% level; Value within parentheses is standard deviation (SD)

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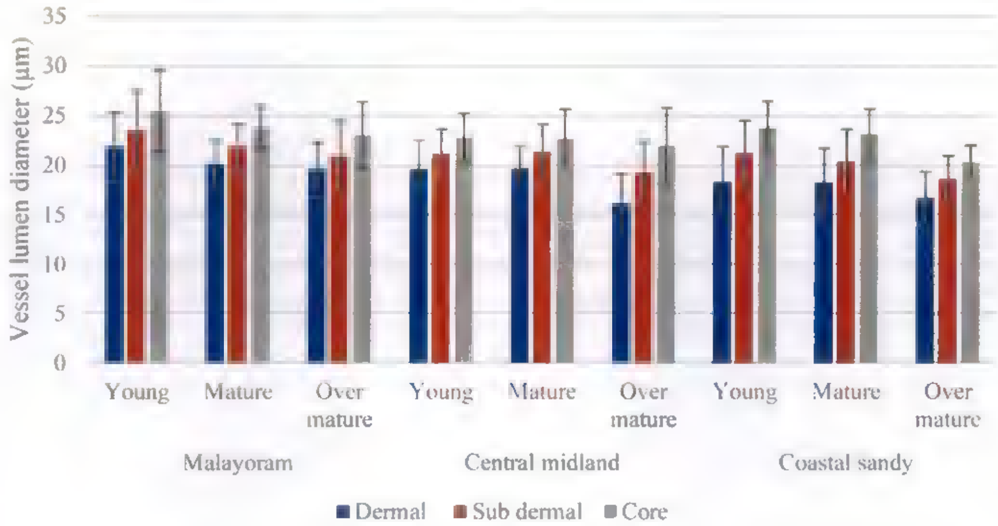

Figure 17. Vessel lumen diameter of coconut palm wood from different agro-climatic zones and age groups

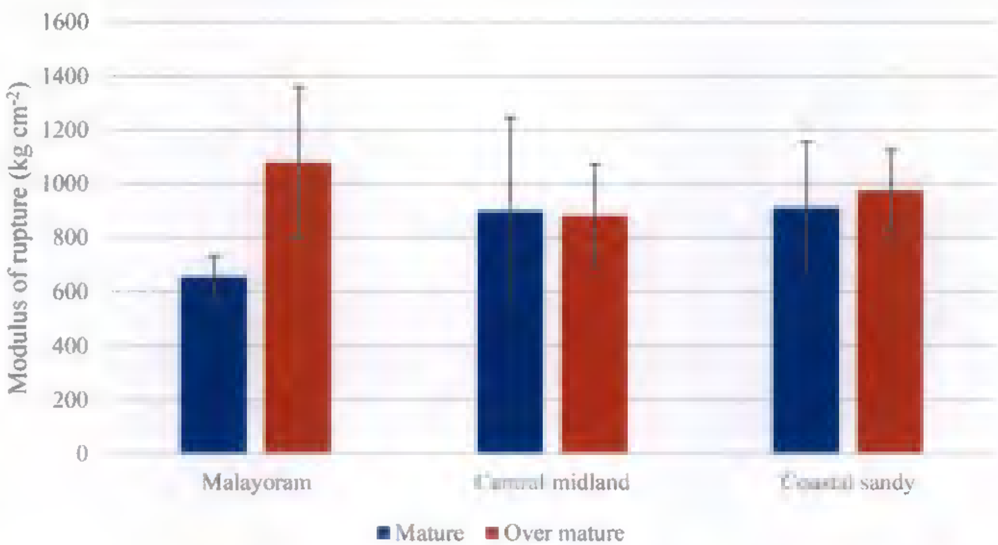

Figure 18. Modulus of rupture of coconut palm wood with density above 650 kg m^{-3}

Analysis of variance showed that there was no significant difference in MOR for coconut palm wood among the agro-climatic zones and the age groups.

4.2.5.1.2. Maximum load

Analysis of variance of maximum load found that there was no significant difference among the agro-climatic zones and the age groups. Mean maximum load of mature palms ranges from 118.17 kg for Malayoram to 162.13 kg for Coastal sandy. On the other hand, for over mature palms maximum load ranges from 154.80 kg (Central midland) to 187.60 kg (Malayoram) (Table 18 and 19).

4.2.5.1.3. Horizontal shear stress at maximum load

Analysis of variance of horizontal shear stress at maximum load (HS at ML) showed no significant difference between the agro-climatic zones and the age groups. HS at ML was maximum (37.36 kg cm^{-2}) for over mature palms from Malayoram and minimum (22.98 kg cm^{-2}) for mature palms from Malayoram (Table 18, 19 and Figure 19).

4.2.5.1.4. Horizontal shear stress at limit of proportionality

Analysis of variance of horizontal shear stress at limit of proportionality (HS at LP) showed no significant difference among the agro-climatic zones and the age groups. HS at LP of mature palm ranges from 13.92 kg cm^{-2} (Malayoram) to 23.35 kg cm^{-2} (Central midland) (Table 18). Table 19. Features HS at LP for over mature palms. It ranges from 23.71 kg cm^{-2} to 25.91 kg cm^{-2} for Central midland and Malayoram respectively (Figure 19).

4.2.5.1.5. Fibre stress at limit of proportionality

Fibre stress at the limit of proportionality (FS at LP) is shown in Table 18 and 19. FS at LP ranges from 396.85 kg cm^{-2} to 670.99 kg cm^{-2} for mature palms from Malayoram and Central midland respectively. For over mature palms FS at LP ranges from 682.19 kg cm^{-2} to 748.53 kg cm^{-2} for Central midland and

Table 18. Test for static bending of mature coconut palm wood with density above 650 kg m^{-3}

Age (years)	Zone	Sample	Static bending					
			MOR (kg cm^{-2})	ML (kg)	HSS at ML (kg cm^{-2})	HSS at LP (kg cm^{-2})	FS at LP (kg cm^{-2})	MOE (kg cm^{-2})
35-45	Malayoram	1	601.49 (102.36)	108.70 (17.73)	21.10 (3.54)	9.73 (9.46)	277.65 (270.40)	42524.36 (3573.55)
		2	708.99 (1.80)	127.63 (1.34)	24.87 (0.11)	18.11 (1.75)	516.05 (48.83)	83048.81 (6292.07)
		Mean	655.24 (76.01)	118.17 (13.38)	22.98 (2.67)	13.92 (5.92)	396.85 (168.57)	62786.59 (28655.11)
	Central midland	1	1077.67 (79.41)	189.19 (11.33)	37.52 (2.72)	31.25 (0.64)	897.56 (19.30)	113060.35 (7949.10)
		2	1144.12 (168.29)	201.39 (32.98)	39.57) (6.52)	31.56 (6.06)	901.05 (174.95)	107534.39 (5872.14)
		3	385.12 (159.70)	67.96 (27.60)	13.42 (5.55)	8.80 (4.38)	252.59 (126.09)	48208.73 (12383.18)
		4	984.59 (134.34)	168.75 (16.77)	33.91 (4.23)	21.79 (2.29)	632.64 (73.83)	116177.10 (46273.29)
		Mean	897.87 (348.04)	156.82 (60.75)	31.10 (12.02)	23.35 (10.71)	670.96 (305.94)	96245.14 (32223.07)
	Coastal sandy	1	1065.25 (395.51)	191.63 (74.17)	37.34 (13.90)	32.23 (10.132	919.59 (288.13)	109823.95 (10868.34)
		2	571.14 (201.02)	103.78 (36.20)	20.10 (7.04)	13.19 (3.33)	375.25 (94.45)	57656.21 (17707.84)

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Cont.

		3	1106.79	190.47	38.37	25.62	739.19	99504.77
			(206.50)	(34.68)	(6.86)	(5.96)	(177.60)	(18036.99)
		4	897.99	162.64	31.53	21.44	610.64	87823.34
			(61.55)	(11.50)	(2.25)	(4.38)	(123.08)	(20.63)
		Mean	910.29	162.13	31.84	23.12	661.17	88702.07
			(243.45)	(41.14)	(8.38)	(7.97)	(228.89)	(22564.35)

Not Significant in both agro-climatic zones and age groups; Value within parentheses is standard deviation (SD)

Table 19. Test for static bending of over mature coconut palm wood with density above 650 kg m^{-3}

Age (years)	Zone	Sample	Static bending					
			MOR ($kg\ cm^{-2}$)	ML (kg)	HSS at ML ($kg\ cm^{-2}$)	HSS at LP ($kg\ cm^{-2}$)	FS at LP ($kg\ cm^{-2}$)	MOE ($kg\ cm^{-2}$)
55-65	Malayoram	1	915.04 (367.83)	159.79 (63.05)	31.58 (12.61)	20.93 (7.39)	606.29 (215.75)	90852.33 (28104.15)
		2	1404.74 (63.91)	243.53 (12.06)	48.73 (2.20)	35.15 (0.91)	1013.25 (26.72)	134027.83 (1533.93)
		3	919.43 (9.43)	159.48 (4.37)	31.77 (0.60)	21.65 (4.06)	626.06 (112.01)	102623.44 (3316.27)
		Mean	1079.74 (281.47)	187.60 (48.44)	37.36 (9.84)	25.91 (8.01)	748.54 (229.47)	109167.87 (22319.35)
	Central midland	1	1012.47 (261.03)	182.30 (47.70)	35.51 (9.22)	24.00 (12.58)	684.09 (357.47)	96147.12 (22122.39)
		2	906.36 (326.87)	165.15 (58.67)	31.96 (11.45)	26.30 (5.56)	745.61 (159.37)	101686.78 (7946.88)
		3	839.53 (141.44)	145.49 (23.57)	29.00 (4.82)	18.73 (0.26)	542.11 (8.60)	89656.56 (3636.27)
		4	679.64 (125.37)	118.74 (23.31)	23.56 (4.48)	18.03 (2.42)	520.25 (66.67)	70314.45 (8206.87)
		5	779.10 (92.60)	134.13 (14.97)	26.89 (3.22)	23.30 (2.89)	674.94 (83.07)	108553.29 (15811.91)
		6	1049.75 (395.60)	181.52 (64.26)	36.23 (13.22)	28.02 (5.82)	811.12 (178.47)	108891.66 (29734.69)

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Cont.

		7	1090.11 (96.67)	190.93 (15.83)	37.83 (3.29)	31.95 (0.21)	920.74 (7.85)	106722.74 (3707.32)
		8	1043.13 (418.84)	182.92 (75.53)	36.24 (14.67)	30.04 (12.87)	865.98 (365.47)	107555.73 (26466.63)
		9	527.45 (79.71)	92.00 (12.68)	18.24 (2.69)	13.02 (2.81)	374.80 (83.21)	88822.53 (128.31)
		Mean	880.84 (191.72)	154.80 (34.34)	30.61 (6.71)	23.71 (6.17)	682.18 (177.38)	97594.54 (12909.65)
	Coastal sandy	1	1110.29 (99.14)	204.87 (9.53)	39.24 (3.00)	31.39 (7.02)	889.03 (210.82)	112667.47 (27349.96)
		2	1038.22 (36.31)	188.00 (6.88)	36.60 (0.61)	22.68 (1.14)	648.88 (12.19)	95817.60 (5698.45)
		3	984.50 (32.00)	173.68 (5.83)	34.27 (1.15)	24.18 (3.80)	694.61 (108.36)	93013.34 (7863.75)
		4	770.45 (236.79)	136.41 (41.74)	26.86 (8.18)	20.56 (8.57)	590.02 (247.49)	85500.86 (17242.91)
		Mean	975.86 (146.32)	175.74 (29.16)	34.24 (5.33)	24.70 (4.70)	705.64 (129.54)	96749.82 (11470.85)

Not Significant in both agro-climatic zones and age groups; Value within parentheses is standard deviation (SD)

116

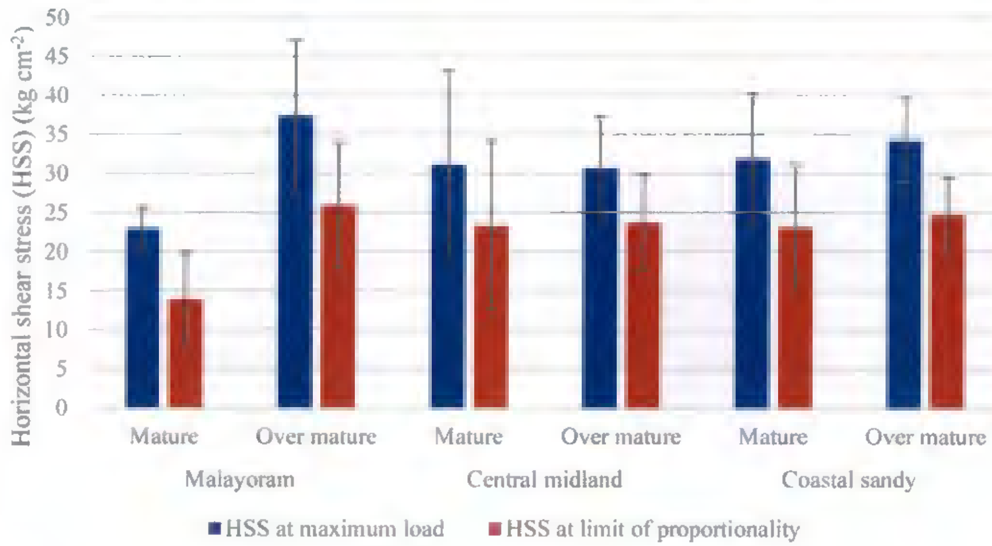

Figure 19. Horizontal shear stress of coconut palm wood with density above 650 kg m^{-3}

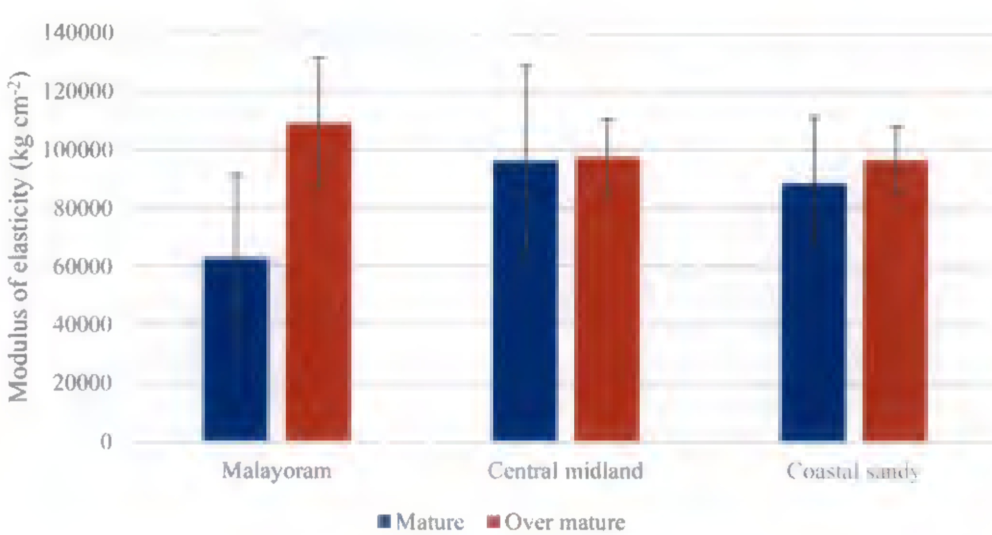

Figure 20. Modulus of elasticity of coconut palm wood with density above 650 kg m^{-3}

Malayoram respectively. Analysis of variance showed that there was no significant difference between the agro-climatic zones and the age groups.

4.2.5.1.5. Modulus of elasticity

Modulus of elasticity (MOE) of the coconut palms was shown in Table 18 and 19. MOE ranges from 62786.59 kg cm^{-2} (Malayoram) to 96245.14 kg cm^{-2} (Central midland) for mature palms. For over mature palms MOE ranges from 96749.82 kg cm^{-2} (Coastal sandy) to 109167.87 kg cm^{-2} (Malayoram). Analysis of variance showed that there was no significant difference in MOE for coconut palm wood between the agro-climatic zones and the age groups (Figure 20).

4.2.5.2. Test for compression strength parallel to grain

4.2.5.2.1. Maximum load

The maximum load had no significant difference between the agro-climatic zones and between the age groups showed a significant difference. Mean maximum load for the palms ranges from 1418.31 kg (mature palms from Malayoram) to 2723.13 kg for (over mature palms from Coastal sandy) (Table 20 and 21).

4.2.5.2.1.1. Compressive stress at limit of proportionality

Analysis of variance showed that there was no significant difference between the agro-climatic zones and the age groups. Compressive stress at the limit of proportionality (CS at LP) ranges from 258.20 kg cm^{-2} (Malayoram) to 445.53 kg cm^{-2} (Coastal sandy) for mature palms. For over mature palms CS at LP ranges from 434.72 kg cm^{-2} (Malayoram) to 534.69 kg cm^{-2} (Coastal sandy) (Table 20, 21 and Figure 21).

4.2.5.2.1.2. Compressive stress at maximum load

Analysis of variance of compressive stress at maximum load (CS at ML) showed no significant difference between the agro-climatic zones and there is a significant difference between the age groups. CS at ML of mature palm ranges from 368.00 kg cm^{-2} (Malayoram) to 550.22 kg cm^{-2} (Central midland) (Table 20).

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Table 20. Compression parallel to grain for mature coconut palm wood with density above 650 kg m^{-3}

Age (years)	Zone	Sample	Compression parallel to grain			
			ML (kg) *	CS at LP (kg cm^{-2})	CS at ML (kg cm^{-2}) *	MOE (kg cm^{-2})
35-45	Malayoram	1	1651.18 (65.58)	299.51 (0.49)	430.12 (15.69)	28907.49 (1524.92)
		2	1185.43 (102.92)	216.89 (46.68)	305.88 (25.68)	24543.03 (4558.27)
		Mean	1418.31 (329.34)	258.20 (58.42)	368.00 (87.85)	26725.26 (3086.13)
	Central midland	1	2235.32 (256.86)	501.92 (170.99)	572.27 (83.21)	58120.74 (26212.23)
		2	2228.49 (154.06)	422.07 (58.92)	583.21 (40.10)	45137.49 (1374.87)
		3	1609.09 (242.78)	335.66 (71.11)	422.64 (65.28)	38131.52 (8451.86)
		4	2383.35 (312.23)	422.32 (57.05)	622.75 (78.46)	49401.40 (10664.52)
		Mean	2114.06 (344.14)	420.49 (67.90)	550.22 (87.78)	47697.79 (8358.81)
	Coastal sandy	1	2386.29 (141.52)	464.25 (10.69)	611.84 (38.47)	46970.24 (7711.92)
		2	1612.34 (573.46)	303.83 (41.87)	418.80 (149.80)	45870.39 (17139.39)
		3	2797.75 (33.26)	544.61 (59.07)	746.46 (6.14)	54140.96 (312.29)

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Cont.

		4	1587.40 (14.56)	469.44 (257.22)	421.07 (11.80)	55554.21 (38400.26)
		Mean	2095.94 (597.03)	445.54 (101.35)	549.54 (159.43)	50633.95 (4920.11)

** Significant in age groups at 5 % level; Value within parentheses is standard deviation (SD)*

Table 21. Compression parallel to grain for over mature coconut palm wood with density above 650 kg m^{-3}

Age (years)	Zone	Sample	Compression parallel to grain			
			ML (kg)*	CS at LP (kg cm^{-2})	CS at ML (kg cm^{-2}) *	MOE (kg cm^{-2})
55-65	Malayoram	1	2213.88 (123.92)	327.50 (123.92)	596.68 (188.38)	37023.56 (27.71)
		2	3168.11 (29.43)	520.80 (29.43)	837.88 (101.91)	53176.40 (4.13)
		3	2293.86 (31.90)	455.86 (31.90)	606.82 (12.91)	48421.00 (7.77)
		Mean	2558.62 (529.35)	434.72 (98.37)	680.46 (136.42)	46206.99 (8300.89)
	Central midland	1	2156.90 (181.73)	436.60 (40.47)	564.62 (50.63)	41949.21 (5653.84)
		2	1564.75 (28.80)	249.40 (28.80)	406.92 (14.95)	30054.52 (8.66)
		3	2637.07 (8.06)	489.65 (8.06)	686.64 (74.66)	46576.51 (3.84)
		4	1694.95 (199.55)	322.32 (199.55)	435.66 (47.99)	37780.50 (66.75)
		5	2622.47 (927.17)	431.27 (927.17)	695.77 (29.12)	39229.25 (247.17)
		6	2076.91 (81.57)	399.83 (81.57)	552.05 (24.21)	44857.47 (24.29)

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Cont.

		7	2768.00 (167.36)	542.29 (167.36)	732.76 (4.51)	51108.09 (42.17)
		8	3411.30 (115.29)	722.38 (115.29)	923.81 (29.93)	72677.78 (19.64)
		9	2079.95 (105.00)	471.31 (105.00)	546.88 (11.58)	54642.76 (28.60)
		Mean	2334.70 (579.45)	451.67 (134.30)	616.12 (161.04)	46541.79 (12224.77)
	Coastal sandy	1	3166.15 (94.75)	646.07 (94.75)	820.64 (53.44)	70295.94 (26.03)
		2	2837.44 (10.42)	544.02 (10.42)	753.16 (41.24)	56516.85 (7.70)
		3	2626.06 (181.93)	492.57 (181.93)	698.91 (56.71)	54392.95 (50.46)
		4	2262.87 (157.10)	456.11 (157.10)	598.14 (21.73)	47695.80 (40.65)
		Mean	2723.13 (378.85)	534.69 (82.55)	717.71 (93.99)	57225.38 (9489.94)

** Significant in age groups at 5 % level; Value within parentheses is standard deviation (SD)*

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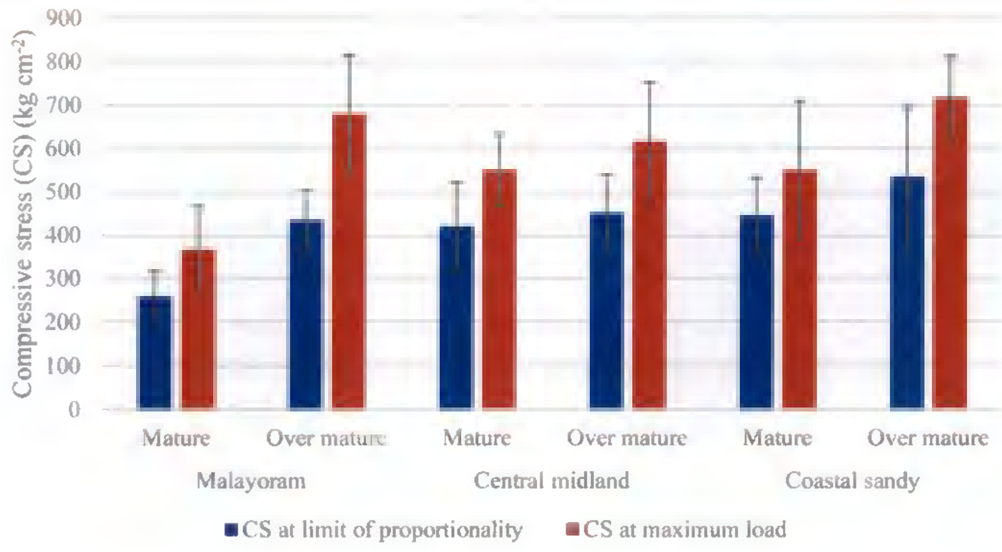

Figure 21. Compressive stress parallel to grain of coconut palm wood with density above 650 kg m^{-3}

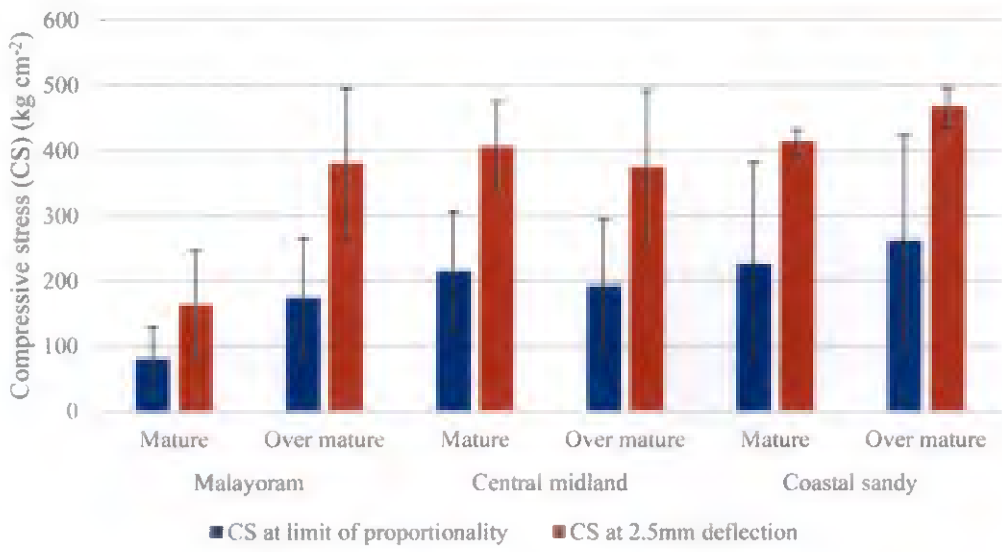

Figure 22. Compressive stress perpendicular to grain of coconut palm wood with density above 650 kg m^{-3}

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Table 21 features CS at ML for over mature palms. It ranges from 616.12 kg cm^{-2} to717.71 kg cm^{-2} for Central midland and Coastal sandy respectively (Figure 21).

4.2.5.2.1.3. Modulus of elasticity

Modulus of elasticity (MOE) of the coconut palms was shown in Table 20 and 21. MOE ranges from 26725.26 kg cm^{-2} (Malayoram) to 50633.95 kg cm^{-2} (Coastal sandy) for mature palms. For over mature palms MOE ranges from 46206.99 kg cm^{-2} (Malayoram) to 57225.38 kg cm^{-2} (Coastal sandy). Analysis of variance showed that there is no significant difference in MOE for coconut palm wood between the agro-climatic zones and the age groups.

4.2.5.3. Test for compression strength perpendicular to grain

4.2.5.3.1. Compressive stress at limit of proportionality

Analysis of variance of compressive stress at limit of proportionality (CS at LP) found that there was no significant difference between the agro-climatic zones and the age groups. CS at LP of mature palms ranges from 80.21 kg cm^{-2} for Malayoram to 226.18 kg cm^{-2} for Coastal sandy. On the other hand, for over mature palms CS at LP ranges from 174.49 kg cm^{-2} (Malayoram) to 262.28 kg cm^{-2} (Coastal sandy) (Table 22, 23 and Figure 22).

4.2.5.3.2. Compressive stress at 2.5 mm limit

Compressive stress at 2.5 mm (CS at 2.5 mm) deflection limit ranged from 163.69 kg cm^{-2} (Malayoram) to 413.44 kg cm^{-2} (Coastal sandy) for mature palms (Table 22). From Table 23, for over mature palms CS at 2.5 mm limit ranged from 374.27 kg cm^{-2} (Central midland) to 465.66 kg cm^{-2} (Coastal sandy) (Figure 22). Analysis of variance showed that there is no significant difference in CS at 2.5 mm limit for coconut palm wood between the agro-climatic zones and the age groups.

4.2.5.3.3. Modulus of elasticity

The maximum mean modulus of elasticity (MOE) of mature palms was 31592.30 kg cm^{-2} and the minimum mean MOE was 15545.39 kg cm^{-2} for Coastal

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Table 22. Compression perpendicular to grain for mature coconut palm wood with density above 650 kg m^{-3}

Age (years)	Zone	Sample	Compression perpendicular to grain		
			CS at LP (kg cm^{-2})	CS at 2.5 mm (kg cm^{-2})	MOE (kg cm^{-2})
35-45	Malayoram	1	115.22 (60.17)	235.33 (50.42)	22342.16 (3818.97)
		2	45.20 (9.02)	92.06 (5.44)	8748.62 (1391.94)
		Mean	80.21 (49.51)	163.69 (101.31)	15545.39 (9612.08)
	Central midland	1	218.40 (37.91)	437.97 (61.85)	34124.83 (5923.09)
		2	264.98 (24.47)	473.42 (8.19)	36261.16 (1946.35)
		3	84.84 (7.82)	180.56 (10.52)	14444.68 (3685.73)
		4	293.32 (10.34)	530.82 (22.64)	30804.24 (1882.17)
		Mean	215.39 (92.35)	405.69 (154.89)	28908.73 (9900.64)
	Coastal sandy	1	312.68 (42.37)	558.31 (2.94)	46017.07 (467.92)
		2	104.54 (43.35)	192.70 (66.20)	16459.03 (5260.14)
		3	278.32 (4.95)	496.44 (3.92)	31747.34 (2498.45)
		4	209.18 (17.16)	406.32 (30.32)	32145.75 (2586.32)
		Mean	226.18 (91.81)	413.44 (159.85)	31592.30 (12075.05)

Not Significant in both agro-climatic zones and age groups; Value within parentheses is standard deviation (SD)

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Table 23. Compression perpendicular to grain for over mature coconut palm wood with density above 650 kg m^{-3}

Age (years)	Zone	Sample	Compression perpendicular to grain		
			CS at LP (kg cm^{-2})	CS at 2.5 mm (kg cm^{-2})	MOE (kg cm^{-2})
55-65	Malayoram	1	109.53 (36.83)	303.38 (59.82)	17176.80 (9345.30)
		2	267.65 (63.61)	511.37 (83.67)	36979.94 (10862.25)
		3	146.28 (41.40)	327.19 (31.48)	22811.52 (833.24)
		Mean	174.49 (82.75)	380.65 (113.84)	25656.09 (10203.42)
	Central midland	1	139.92 (1.14)	303.40 (19.14)	26447.52 (4058.94)
		2	97.25 (24.09)	199.44 (27.03)	17750.69 (966.22)
		3	290.47 (14.58)	582.34 (10.24)	42209.73 (2213.27)
		4	187.88 (34.41)	347.14 (45.23)	28584.46 (3710.15)
		5	179.03 (51.31)	381.45 (66.04)	27697.89 (3121.01)
		6	136.82 (51.88)	299.33 (69.54)	19607.71 (3727.92)
		7	302.84 (45.43)	526.15 (86.82)	44520.98 (200.12)
		8	190.87 (43.71)	386.43 (26.89)	32798.28 (1138.68)
		9	208.77 (3.87)	342.75 (7.25)	32135.04 (4407.50)
		Mean	192.65 (68.17)	374.27 (116.99)	30194.70 (9013.55)
	Coastal sandy	1	248.38 (182.51)	429.22 (276.07)	38606.67 (22759.86)
		2	281.59 (11.14)	501.45 (34.50)	31085.48 (3640.02)
		3	273.17 (26.69)	472.11 (0.10)	29874.58 (2150.92)
		4	246.00 (45.41)	459.86 (116.20)	31499.18 (7203.45)
		Mean	262.28 (17.80)	465.66 (29.91)	32766.48 (3954.02)

Not Significant in both agro-climatic zones and age groups; Value within parentheses is standard deviation (SD)

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Table 24. Hardness of mature coconut palm wood with density above 650 kg m^{-3}

Age (years)	Zone	Sample	Hardness	
			Side (kg)	**End (kg)**
35-45	**Malayoram**	1	601.04 (150.26)	631.64 (75.63)
		2	270.45 (4.94)	280.50 (67.00)
		Mean	435.75 (233.76)	456.07 (248.29)
	Central midland	1	910.61 (133.97)	748.87 (249.27)
		2	797.98 (359.76)	720.58 (52.62)
		3	413.64 (10.72)	575.65 (60.76)
		4	1035.79 (57.04)	910.33 (0.05)
		Mean	789.50 (268.74)	738.85 (137.20)
	Coastal sandy	1	886.50 (311.58)	554.32 (233.01)
		2	701.31 (8.70)	722.43 (80.37)
		3	1137.80 (73.33)	688.93 (41.75)
		4	1099.55 (20.10)	904.45 (210.92)
		Mean	956.29 (202.78)	717.53 (144.24)

Not Significant in both agro-climatic zones and age; Value within parentheses is standard deviation (SD)

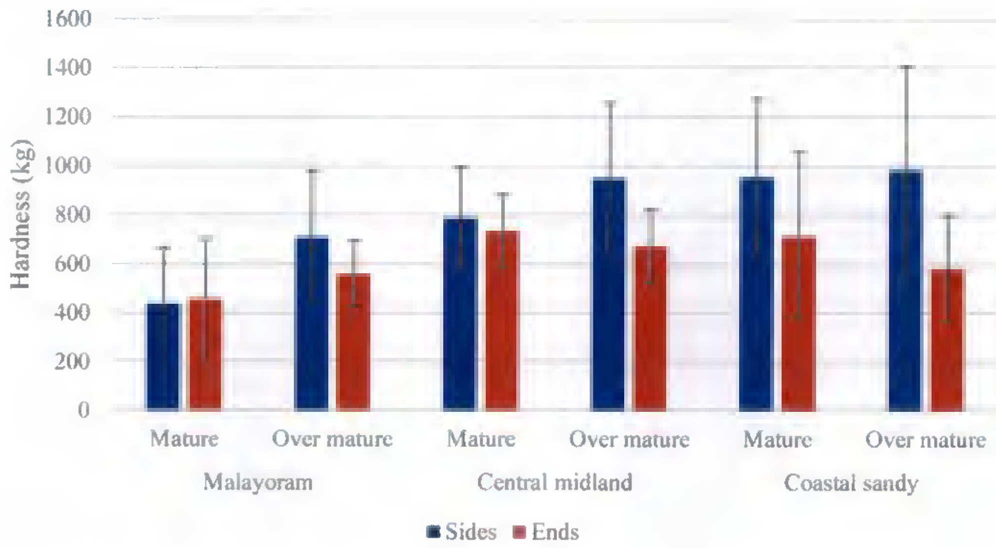

Figure 23. Hardness of coconut palm wood with density above 650 kg m^{-3}

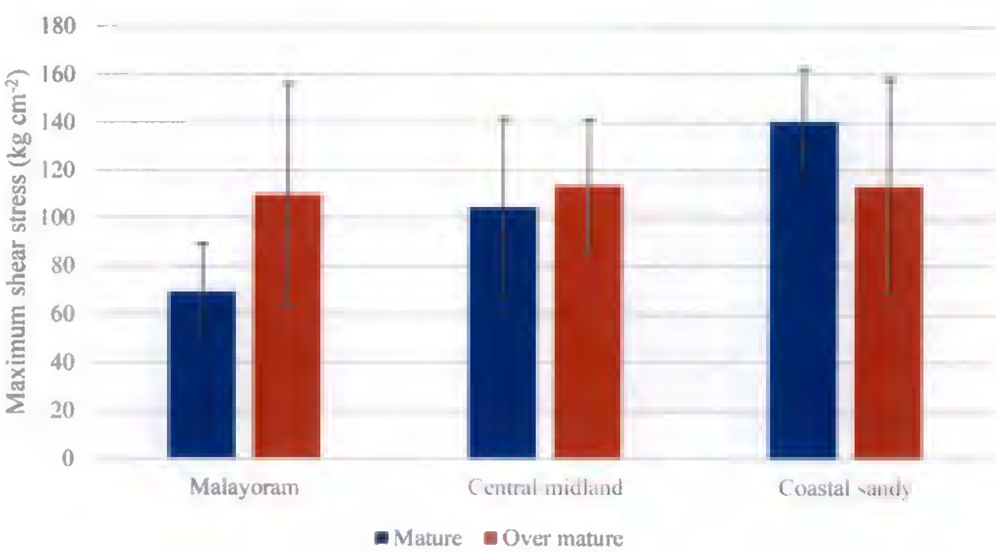

Figure 24. Maximum shear stress of coconut palm wood with density above 650 kg m^{-3}

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sandy and Malayoram respectively (Table 23). For over mature palms, the maximum mean MOE was 32766.48 kg cm^{-2} (Coastal sandy) and the minimum was 25656.09 kg cm^{-2} (Malayoram) (Table 24). Analysis of variance did not reveal any significant difference between the ago-climatic zones and the age groups.

4.2.5.4. Hardness test

4.2.5.4.1. Side

Analysis of variance for hardness at sides showed no significant difference between the agro-climatic zones and between the age groups. Hardness at sides of mature palm ranged from 435.75 kg (Malayoram) to 956.29 kg (Coastal sandy) (Table 24). Table 25 features mean hardness at sides for over mature palms. It ranged from 712.54 kg to 985.85 kg for Malayoram and Coastal sandy respectively (Figure 23).

4.2.5.4.2. End

Hardness at ends ranged from 456.07 kg (Malayoram) to 738.85 kg (Central midland) for mature palms (Table 24). From Table 25, for over mature palms hardness at ends ranges from 374.27 kg (Central midland) to 465.66 kg (Coastal sandy). Analysis of variance showed that there was no significant difference in end hardness for coconut palm wood between the agro-climatic zones and the age groups (Figure 23).

4.2.5.5. Shear strength

4.2.5.5.1. Maximum load

Analysis of variance of maximum load found that there was no significant difference among the agro-climatic zones and the age groups. Maximum load of mature palms ranges from 1733.04 kg for Malayoram to 3508.16 kg for Coastal sandy. For over mature palms maximum load ranges from 2754.08 kg (Malayoram) to 2842.82 kg (Central midland) (Table 26 and 27).

Table 25. Hardness of over mature coconut palm wood with density above 650 kg m^{-3}

Age (years)	Zone	Sample	Hardness	
			Side (kg)	End (kg)
55-65	Malayoram	1	594.16 (142.61)	729.91 (120.87)
		2	1058.76 (128.88)	448.49 (265.60)
		3	484.70 (66.84)	503.68 (94.44)
		Mean	712.54 (304.79)	560.69 (149.12)
	Central midland	1	711.94 (129.17)	892.60 (41.83)
		2	620.07 (117.75)	764.94 (78.14)
		3	1567.89 (121.04)	1138.52 (75.43)
		4	904.51 (137.65)	662.60 (424.97)
		5	1026.41 (164.18)	470.92 (236.56)
		6	661.18 (211.46)	219.04 (75.82)
		7	863.36 (64.82)	798.22 (104.05)
		8	1340.44 (229.98)	990.47 (81.13)
		9	870.00 (389.16)	140.80 (52.13)
		Mean	951.75 (317.21)	675.34 (339.13)
	Coastal sandy	1	1146.05 (10.31)	366.68 (55.59)
		2	1324.40 (36.71)	650.16 (427.28)
		3	368.27 (26.30)	460.43 (10.85)
		4	1104.68 (260.48)	861.80 (202.28)
		Mean	985.85 (422.62)	584.77 (219.12)

Not Significant in both agro-climatic zones and age groups; Value within parentheses is standard deviation (SD)

Table 26. Shear strength of mature coconut palm wood with density above 650 kg m^{-3}

Age (years)	Zone	Sample	Shear strength	
			MSS (kg cm^{-2})	ML (kg)
35-45	**Malayoram**	1	83.40 (8.22)	2085.06 (205.41)
		2	55.24 (21.14)	1381.03 (528.66)
		Mean	69.32 (19.91)	1733.04 (497.82)
	Central midland	1	85.23 (7.75)	2130.80 (193.73)
		2	106.02 (2.26)	2650.37 (56.36)
		3	71.51 (9.50)	1787.70 (237.51)
		4	155.95 (6.54)	3898.60 (163.60)
		Mean	104.68 (37.01)	2616.86 (925.16)
	Coastal sandy	1	146.70 (23.49)	3667.61 (587.20)
		2	115.62 (2.18)	2890.46 (54.53)
		3	167.77 (2.54)	4194.06 (63.51)
		4	131.22 (2.84)	3280.52 (70.99)
		Mean	140.33 (22.26)	3508.16 (556.55)

Not Significant in both agro-climatic zones and age groups; Value within parentheses is standard deviation (SD)

Table 27. Shear strength of mature coconut palm wood with density above 650 kg m^{-3}

Age (years)	Zone	Sample	Shear strength	
			MSS (kg cm^{-2})	ML (kg)
55-65	**Malayoram**	1	73.09 (5.71)	1827.24 (142.70)
		2	161.67 (9.37)	4041.55 (234.26)
		3	95.74 (14.38)	2393.45 (359.48)
		Mean	110.17 (46.02)	2754.08 (1150.36)
	Central midland	1	109.91 (3.76)	2747.87 (94.04)
		2	73.52 (5.11)	1838.44 (128.62)
		3	151.71 (11.48)	3792.83 (287.01)
		4	106.15 (21.02)	2653.81 (525.34)
		5	132.55 (18.26)	3313.84 (456.48)
		6	120.81 (27.41)	3020.24 (685.29)
		7	120.43 (14.96)	3010.80 (374.13)
		8	138.77 (10.64)	3469.27 (265.86)
		9	69.53 (0.27)	1738.25 (6.62)
		Mean	113.71 (27.75)	2842.82 (693.73)
	Coastal sandy	1	162.11 (31.33)	4052.83 (783.08)
		2	117.18 (7.72)	2929.60 (193.02)
		3	54.12 (7.10)	1352.99 (177.46)
		4	120.46 (9.61)	3011.47 (240.21)
		Mean	113.47 (44.54)	2836.72 (1113.49)

Not Significant in both agro-climatic zones and age groups; Value within parentheses is standard deviation (SD)

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4.2.5.5.2. Maximum shear stress

Form Table 26 and 27 maximum shear stress (MSS) of coconut palms varies from 69.32 kg cm^{-2} to 140.33 kg cm^{-2}. Analysis of variance showed that there was no significant difference between the agro-climatic zones and the age groups. MSS for mature palms ranged from 69.32 kg cm^{-2} (Malayoram) to 140.33 kg cm^{-2} (Coastal sandy) and for over mature palms MSS ranged from 110.17 kg cm^{-2} to 113.71 kg cm^{-2} for Malayoram and Central midland respectively (Figure 24).

4.2.5.6. Tensile strength perpendicular to grain

4.2.5.6.1. Maximum load

Analysis of variance of maximum load found that there was no significant difference among the agro-climatic zones and the age groups. Maximum load of mature palms ranged from 123.84 kg for Malayoram to 151.37 kg for Central midland. For over mature palms maximum load ranged from 99.99 kg (Malayoram) to 177.16 kg (Central midland) (Table 28 and 29).

4.2.5.6.2. Maximum tensile strength

Maximum tensile strength ranged from 12.89 kg cm^{-2} (Coastal sandy) to 15.78 kg cm^{-2} (Central midland) for mature palms (Table 28). From Table 29, for over mature palms maximum tensile strength ranged from 10.22 kg cm^{-2} (Malayoram) to 18.52 kg cm^{-2} (Central midland). Analysis of variance showed that there is no significant difference in maximum tensile strength for coconut palm wood among the agro-climatic zones and the age groups (Figure 25).

4.2.5.7. Tensile strength parallel to grain

4.2.5.7.1. Maximum load

Maximum load of mature palms ranged from 234.48 kg to 267.53 kg for Central midland and Malayoram respectively (Table 30) and for over mature palms maximum load ranged from 306.90 kg (Coastal sandy) to 415.86 kg (Malayoram) (Table 31). Analysis of variance showed that there was no significant difference between in maximum load between the agro-climatic zones and the age groups.

Table 28. Tensile strength perpendicular to grain for mature coconut palm wood with density above 650 kg m^{-3}

Age	Zone	Sample	Tensile strength perpendicular to grain	
			ML (kg)	**MTS (kg cm^{-2})**
35-45	**Malayoram**	1	217.64 (14.31)	21.77 (1.44)
		2	70.3 (1.07)	7.77 (0.11)
		Mean	143.97 (104.19)	14.77 (9.90
	Central midland	1	197.12 (47.45)	20.76 (5.02)
		2	137.15 (33.14)	14.24 (3.34)
		3	92.43 (11.878	9.30 (1.27)
		4	178.80 (54.41)	18.84 (5.79)
		Mean	151.37 (46.62)	15.78 (5.12)
	Coastal sandy	1	131.83 (11.48)	13.18 (1.15)
		2	96.82 (41.11)	10.21 (4.53)
		3	102.71 (34.25)	10.43 (3.39)
		4	164.00 (39.37)	17.72 (5.59)
		Mean	123.84 (30.84)	12.89 (3.50)

Not Significant in both agro-climatic zones and age groups; Value within parentheses is standard deviation (SD)

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Table 29. Tensile strength perpendicular to grain for over mature coconut palm wood with density above 650 kg m^{-3}

Age (years)	Zone	Sample	Tensile perpendicular to grain	
			ML (kg)	MTS (kg cm^{-2})
55-65	Malayoram	1	434.12 (47.16)	811.91 (49.55)
		2	297.19 (56.78)	591.00 (142.47)
		3	516.35 (67.31)	932.52 (97.28)
		Mean	415.89 (110.71)	778.48 (173.20)
	Central midland	1	536.38 (70.55)	1088.92 (125.90)
		2	285.59 (24.95)	551.06 (61.87)
		3	251.55 (25.82)	493.07 (14.10)
		4	318.19 (60.22)	616.45 (107.42)
		5	442.01 (45.96)	842.04 (184.64)
		6	257.26 (15.25)	557.16 (13.18)
		7	513.24 (184.48)	964.47 (406.76)
		8	731.90 (31.96)	1333.93 (64.91)
		9	273.48 (206.45)	598.90 (456.21)
		Mean	401.06 (166.41)	782.89 (292.41)
	Coastal sandy	1	364.92 (107.20)	754.63 (230.76)
		2	505.99 (24.54)	1008.91 (124.13)
		3	125.22 (2.35)	251.98 (1.45)
		4	231.47 (107.72)	429.89 (183.32)
		Mean	306.90 (165.02)	611.35 (336.98)

Not Significant in both agro-climatic zones and age groups; Value within parentheses is standard deviation (SD)

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Table 30. Tensile strength parallel to grain for mature coconut palm wood with density above 650 kg m^{-3}

Age (years)	Zone	Sample	Tensile strength parallel to grain ML (kg)	TS at ML (kg cm^{-2})
35-45	Malayoram	1	217.64 (14.31)	21.77 (1.44)
		2	70.30 (1.08)	7.77 (0.11)
		Mean	143.97 (104.19)	14.77 (9.90)
	Central midland	1	197.12 (47.45)	20.76 (5.02)
		2	137.15 (33.14)	14.24 (3.34)
		3	92.43 (11.88)	9.30 (1.27)
		4	178.80 (54.41)	18.84 (5.79)
		Mean	151.37 (46.62)	15.78 (5.12)
	Coastal sandy	1	131.83 (11.48)	13.18 (1.15)
		2	96.82 (41.11)	10.21 (4.53)
		3	102.71 (34.25)	10.43 (3.39)
		4	163.99 (39.37)	17.72 (5.59)
		Mean	123.84 (30.84)	12.89 (3.50)

Not Significant in both agro-climatic zones and age groups; Value within parentheses is standard deviation (SD)

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Table 31. Tensile strength parallel to grain for over mature coconut palm wood with density above 650 kg m^{-3}

Age (years)	Zone	Sample	Tensile strength parallel to grain	
			ML (kg)	TS at ML (kg cm^{-2})
55-65	Malayoram	1	111.75 (49.23)	11.76 (4.82)
		2	114.49 (7.14)	11.45 (0.72)
		3	73.76 (5.27)	7.46 (0.49)
		Mean	100.00 (22.77)	10.22 (2.40)
	Central midland	1	75.34 (11.99)	7.75 (1.32)
		2	217.01 (32.85)	23.60 (3.57)
		3	150.85 (20.66)	15.87 (2.37)
		4	190.97 (24.99)	20.20 (2.55)
		5	126.56 (75.44)	13.04 (7.96)
		6	197.41 (36.95)	21.51 (5.01)
		7	333.12 (50.52)	33.31 (5.05)
		8	165.38 (3.97)	17.29 (0.38)
		9	138.01 (6.32)	14.14 (1.03)
		Mean	177.16 (72.30)	18.52 (7.33)
	Coastal sandy	1	81.92 (16.52)	8.52 (1.89)
		2	103.32 (71.36)	11.09 (8.19)
		3	147.44 (37.79)	15.47 (4.22)
		4	202.38 (44.15)	21.60 (4.02)
		Mean	133.76 (53.26)	14.17 (5.73)

Not Significant in both agro-climatic zones and age groups Value within parentheses is standard deviation (SD)

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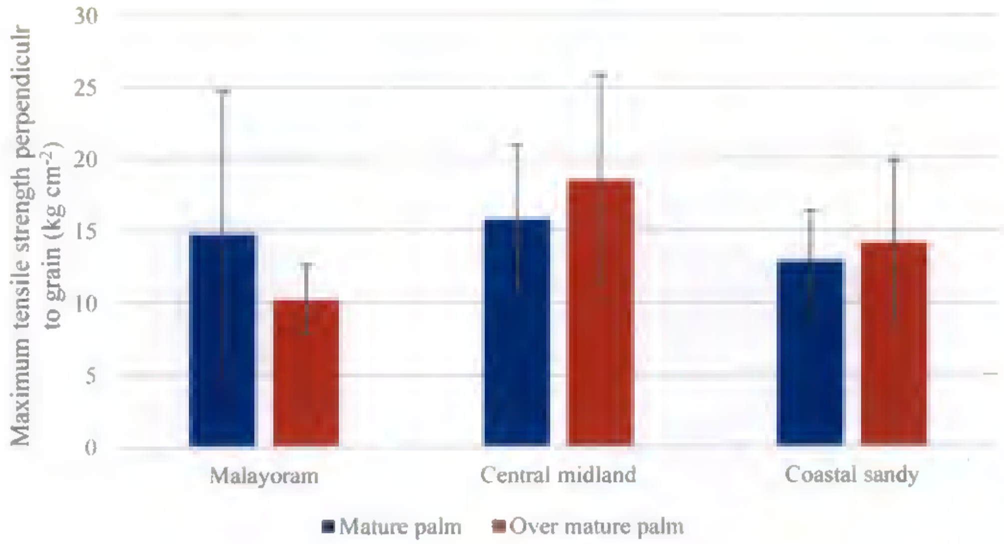

Figure 25. Maximum tensile strength perpendicular to grain of coconut palm wood with density above 650 kg m^{-3}

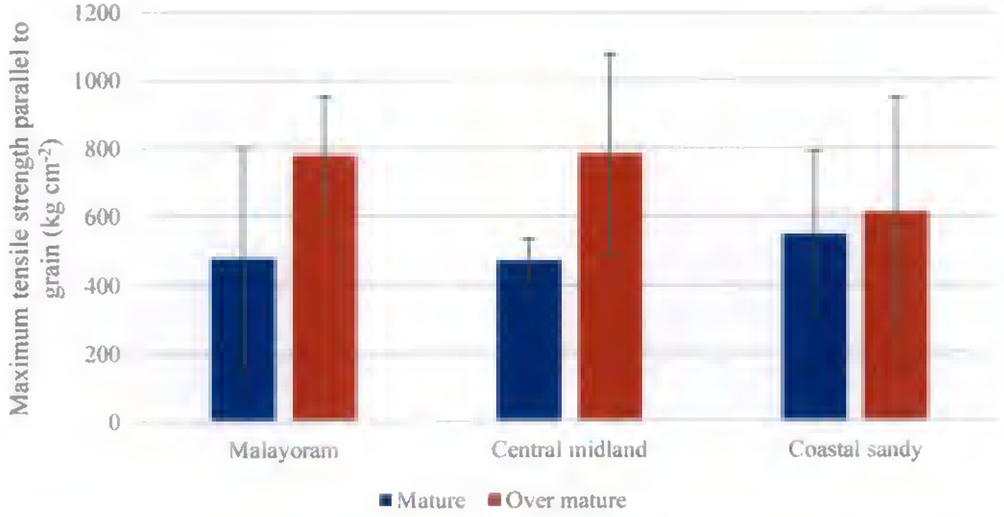

Figure 26. Maximum tensile strength parallel to grain of coconut palms with density above 650 kg m^{-3}

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4.2.5.7.2. Maximum tensile strength

Maximum tensile strength ranges from 470.38 kg cm^{-2} (Central midland) to 547.59 kg cm^{-2} (Coastal sandy) for mature palms (Table 30). From Table 31, for over mature palms Maximum tensile strength ranged from 611.35 kg cm^{-2} (Coastal sandy) to 778.48 kg cm^{-2} (Malayoram) (Figure 26). Analysis of variance showed that there was no significant difference in maximum tensile strength for coconut palm wood between the agro-climatic zones and the age groups.

4.2.6. Interrelationship between wood properties

Table 32 and 33 give correlation coefficient between different wood properties of young, mature and over mature coconut palms from three different agro-climatic zones. Basic density was positively related to vascular bundle frequency, bundle sheath thickness, vascular bundle percentage, fibre length, fibre diameter and fibre wall thickness. Basic density was also correlated to all mechanical properties tested except for compression strength at limit of proportionality in test for compression perpendicular to grain, tensile strength perpendicular to grain, tensile strength at maximum load in test for tensile strength parallel to grain and hardness at ends. On the other hand, basic density was negatively related to moisture content, shrinkage and fibre lumen diameter.

Moisture content was positively correlated with volumetric shrinkage, vascular bundle diameter, fibre length and fibre lumen diameter; negatively correlated to vascular bundle frequency, vascular bundle sheath thickness, vascular bundle percentage, fibre diameter and fibre wall thickness.

The physical and anatomical properties showed a good correlation to each other. On the other fibre wall thickness (anatomical property) did not show correlation with mechanical properties except a positive correlation for compressive stress at maximum load parallel to grain.

Table 32. Correlation coefficient for the interrelationship between physical and anatomical wood properties of coconut palm

	BD	MC	VS	VBF	BST	VBD	VBP	FL	FD	FLD
BD	1									
MC	-0.769**	1								
VS	-0.321**	0.590**	1							
VBF	0.741**	-0.666**	-0.236**	1						
BST	0.234**	-0.211**	-0.137	0.330**	1					
VBD	-0.102	0.159*	0.079	-0.414**	-0.321**	1				
VBP	0.727**	-0.599**	-0.213**	0.717**	0.161*	0.246**	1			
FL	-0.628**	0.576**	0.262**	-0.579**	-0.369**	0.204*	-0.491**	1		
FD	0.700**	-0.609**	-0.350**	0.508**	0.291**	-0.108	0.512**	-0.445**	1	
FLD	-0.732**	0.640**	0.355**	-0.561**	-0.241**	0.092	-0.552**	0.590**	-0.507**	1
FWT	0.819**	-0.714**	-0.404**	0.609**	0.310**	-0.116	0.607**	-0.582**	0.906**	-0.824**

** Correlation is significant at the 0.01 level. * Correlation is significant at the 0.05 level.

BD – Basic density; MC – Moisture content; VS – Volumetric shrinkage; VBF – Vascular bundle frequency; BST – Bundle sheath thickness; VBD – Vascular bundle diameter; VBP – Vascular bundle percentage; FL – Fibre length; FD – Fibre diameter; FLD – Fibre lumen diameter; FWT – Fibre wall thickness

Table 33. Correlation coefficient for the interrelationship between density and mechanical wood properties of coconut palm

	BD	FWT	MSS	MOR	HSS	MOE	CSMLPAG	CSLPPG	MTSPAG	MTSPG	HS
BD	1										
FWT	0.577**	1									
MSS	0.453*	0.338	1								
MOR	0.460*	0.289	0.518**	1							
HSS	0.456*	0.288	0.517**	0.999**	1						
MOE	0.486*	0.349	0.477*	0.858**	0.853**	1					
CSMLPAG	0.751**	0.617**	0.599**	0.662**	0.658**	0.639**	1				
CSLPPG	0.386	0.327	0.605**	0.574**	0.570**	0.535**	0.660**	1			
MTSPAG	0.15	-0.087	-0.02	0.068	0.062	0.047	-0.031	0.225	1		
MTSPG	0.372	0.263	0.157	0.212	0.217	0.305	0.356	-0.051	-0.147	1	
HS	0.500**	0.353	0.772**	0.344	0.344	0.359	0.611**	0.647**	0.126	0.196	1
HE	0.204	-0.139	0.307	0.111	0.11	-0.046	0.121	0.234	0.288	0.117	0.475*

** Correlation is significant at the 0.01 level. * Correlation is significant at the 0.05 level.

BD – Basic density; FWT – Fibre wall thickness; MSS – Maximum shear stress; MOR – Modulus of rupture; HSS – Horizontal shear stress; MOE – Modulus of elasticity; CSMLPAG – Compressive stress at maximum load parallel to grain; CSLPPG – Compressive stress at limit of proportionality perpendicular to grain; MTSPAG – Maximum tensile strength parallel to grain; MTSPG - Maximum tensile strength perpendicular to grain; HS - Hardness at sides; HE – Hardness at ends

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DISCUSSION

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V. DISCUSSION

The results of study entitled "Wood property profiling of coconut palms grown in different agro-climatic zones of Thrissur district, Kerala" are discussed hereunder.

The study investigated the physical, anatomical and mechanical properties of coconut palms grown in three agro-climatic (Malayoram, Central midland and Coastal sandy) zones across three different age groups (young (15-25 years), mature (35-45 years) and over mature (55-65 years). The variation in palm wood properties along the radial positions was also studied.

5.1. Coconut palm wood

The volume calculated for the sampled trees across three agro-climatic zones did not show any significant difference, even though the volume the palms from coastal sandy was the highest compared to other agro-climatic zones. However, the trend of volume increases with increasing age was observed.

Studies on estimation of volume increment and biomass production are very scarce since the economic part is nut, not the wood. The increase in volume in palms is somewhat different from that of dicotyledons. In the recent past, with the utilisation of coconut palm wood gaining momentum it was decided to estimate the utilisable portion of the palm trunk i.e. dermal wood. Anoop *et al.* (2011) suggested that coconut palm wood of density above 400 kg m^{-3} is suitable for structural works.

Accordingly, the palm trunk can be divided into dermal, sub dermal and core wood. Table 2 provides the ratio of dermal to core wood and also shows that increase in age does increase the dermal wood percentage. It was also clear that there was no significant difference in the ratio across agro-climatic zones whereas, along the age groups the ratios do vary significantly. It indirectly agrees with the statement that over mature coconut palm wood have higher sawn wood outturn (Gnanaharan and Dhamodaran, 1989).

5.2. Physical properties

As one of the main objectives of the study was to understand and estimate variation in the physical properties of coconut palm wood across the agro-climatic zones, the present work focused on some important physical properties such as basic density, oven dry density, moisture content, volumetric shrinkage and longitudinal shrinkage and dimensional shrinkage.

5.2.1. Density

Basic density is one of the most important wood property which highly correlate with other wood properties and morphological, physiological and ecological characters (Jerome *et al.,* 2006). Generally, the density of palm wood increases from the core of the trunk toward the dermal position. It is also an important factor in determining the mechanical properties of palmwood.

Analysis of the data collected (Table 3 and 4), revealed that basic density and oven dry density of coconut palm wood increases from core to dermal zone which was also significant. This can be attributed to the anomalous secondary thickening of the stem which is the result of overall cell division and cell enlargement in the parenchymatous ground tissues, together with enlargement of the fibers of the vascular bundle sheaths (Tomlinson, 1961). It is also known that cell walls get more additional layers at the bottom of the trunk and in the peripheral zone (Shirley, 2002; Gibson, 2012). These additional layers on walls occur most likely in different amounts in the parenchyma and fiber caps and may explain the increasing trend in basic and oven dry density (Figure 3 and 4). This character is also exhibited by other members of palmaceae like oil palm and date palm (Bakar, 2013).

However, there was no significant difference in density across agro-climatic zones contrary to the finding of Fathi (2014), who compared the density of coconut palm wood from Mexico and Indonesia and concluded that the Indonesian coconut palm wood had a better density. The work suggested that the variation might be due to palm age, palm varieties and/or soil and climate conditions. Yet Hopewell *et al.* (2010) findings in coconut palm wood from Fiji and Samoa islands

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goes along with our finding. Hence, it can be concluded that the distinctive difference in the climatic zones of Mexico and Indonesia, as well as the distinctive genotypic feature, might have been the reason for the variation in density results of Fathi (2014).

The variation in the density along the longitudinal direction of the palm was not assessed in the study because the differences in the densities across the transverse direction of the trunk is higher than along the trunk that can be neglected (Erwinsyah, 2008).

5.2.2. Moisture content

The moisture content profile shows an opposite pattern compared to green dicot wood, with high moisture content in the core, decreasing towards the periphery, contrary to the pattern generally observed in typical green wood (Hopewell *et al.*, 2010).

Moisture content of coconut palm wood varies widely from 50 % to 400 % depending up on the radial position i.e. dermal, sub dermal and core (Kloot, 1952; Arancon, 1997). Usually moisture content increases rapidly - logarithmically - from dermal to core at any given height (Killmann, 1983). Similar sort of result was obtained from the current study (Table 5). The moisture content across position was significant with a minimum value of 34.70 % (dermal wood of over mature palm) with the maximum of 401.90 % (core wood of young palm). The high moisture content makes the wood susceptible to mould and fungi. Hence, determination of moisture content will be a key factor in the utilisation of coconut palm wood.

Figure 5 clearly shows the trend of moisture content gradient across age group and agro-climatic zones did not differ significantly. Studies on comparing moisture content across different site condition are lacking. Yet this trend of non-significant moisture content across agro-climatic zones can be very well justified with a simple negative correlation between density and the moisture content. The inner portions of the trunk are of very low density and have high moisture content and the details are further explained in 5.5 (Hopewell *et al.*, 2010). Interpretation of moisture

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content for utilisation of coconut palm wood will not be complete. As there are no clear scientific facts on sorption behaviour as well as the relation between moisture content and anatomy

5.2.3. Shrinkage

Shrinkage was directly correlated with the parameters viz, oven-dry density, initial moisture content and vascular bundle frequency. As already observed by Richolson and Swarup (1977), there was little difference between tangential and radial shrinkages, on an average, tangential shrinkage was slightly higher than radial shrinkage. The longitudinal shrinkage was very inconsistent, and shrinkage was negligible.

The mixture of high density fibrous bundle caps (1 g cm^{-3}) and low density parenchyma (0.10 g cm^{-3} to 0.25 g cm^{-3}) attributes the non-homogeneous nature of palm wood. Studies by Bakar *et al.* (1998) in coconut palm wood and Prayitno (1995) in oil palm wood are some prominent and pioneering works. The findings of their study are in conformity with our results (Table 6). The volumetric shrinkage was found to be significant across radial positions only. Yet there is no general trend to be visualised as in the case of density or moisture content. Figure 6 shows an increasing trend in volumetric shrinkage across radial position in young (15-25 years) and mature (35-45 years), but the trend becomes irregular in the case of over mature (55-65 years) palm wood (Killmann, 1983). As in the other properties, there was no variation due to agro-climatic zones.

The interesting aspect of volumetric shrinkage is that the age has no influence, compared to dicotyledons. The irregularity in shrinkage is one of the factors that hampers the utilisation of coconut palm wood (Arancon, 1997). Monocotyledons do not show any distinction between radial and tangential planes. So, in the present study both radial and tangential shrinkage has been brought under single section called dimensional shrinkage. Many researchers have propounded and advocated that both shrinkages can be taken as a single entity as there is little difference between tangential and radial shrinkages in the case of coconut palm wood (Richolson and Swarup 1977; Killmann, 1983; Gnanaharan, 1987). Longitudinal

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shrinkage is very low, usually less than 1 %. However, the result of the study is quite different of the thumb rule. The longitudinal shrinkage, as well as dimensional shrinkage, was found to be significant across radial positions i.e. dermal, subdermal and core (Table 7 and 8).

The contradictory values of shrinkage (longitudinal and dimensional shrinkage) can also be seen in Figure 5 and 6 where the standard deviations are very high. Nevertheless, the study clearly demonstrated that the shrinkage is mainly dependent on the position which in turn is dependent on density (further explained in section 5.5). The data from the study shows that maximum longitudinal shrinkage was observed in the core wood across all agro-climatic zones and age groups.

5.3. Anatomical properties

The anatomical properties in the centre and peripheral zones of coconut wood shows higher values than those in oil palm and date palm wood. However, the anatomical properties of date palm wood show higher properties than at the inner zone those in oil and coconut palm wood. This involves thicker fiber walls and an increasing concentration of vascular bundles in the outer zone of the trunk (Killmann and Lim, 1985; Lim and Khoo, 1986; Killmann and Wong, 1988). The results are similar to the findings from Erwinsyah (2008).

5.3.1. Vascular bundle characteristics

Figure 9, 10, 11 and 12 depict the relationship between vascular bundle characteristics and the sample position along the trunk diameter in relation to three agro-climatic zones and three age groups. Usually, vascular bundle frequency varies significantly along the diameter of the trunk. It decreases from dermal to core of the palm. The distribution of vascular bundle per unit area in coconut palm, oil palm and date palm decreases from the outer zone to the inner zone (Fathi, 2014). Similar sort of result is clearly visualised in Figure 9. This trend was seen in all age groups and all agro-climatic zones but there was no significant difference among age groups and agro-climatic zones. (Figure 9). According to

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Gibson (2012), the frequency of vascular bundle, as well as the concentration of fibers within the vascular bundle, is greater in the outer zone of the trunk than in the inner zone. This sort of trend is also observed in oil palm (*Elaeis guineenis)* by previous studies (Lim and Khoo, 1986; Khozirah *et al.*, 1991; Erwinsyah, 2008; Darwis *et al.*, 2013). The number and the total area of the vascular bundle have proven to be good indications for density and most mechanical properties (Bakar, 2013).

In oil palm, the vascular bundles in the central part are large and few but become smaller and closer together towards the periphery which is called centripetal arrangement of vascular bundles. Attempts to understanding coconut palm wood bundle sheath have been done by Parthasarthy and Klootz (1976a) but all these works are preliminary works without providing quantitative data. Table 10, shows the increasing trend in bundle sheath thickness from core to dermal (significant) as well from young to over mature (non-significant) (Figure 10).

Vascular bundle diameter shows significant difference across radial position (Table 11) not in accordance with that of the study by Fathi (2014) who reported that the highest and the lowest mean area of vascular bundles were observed in the outer zone (174.54 mm^2) and the inner zone (49.59 mm^2) (based on 400 mm^2 specimen area) which comprise 44% and 13% percentage of area/volume of the wood, respectively.

Vascular bundle distribution and area of vascular bundles are indicators for density and strength and they can be used for grading (Khozirah *et al.*, 1991; Fruhwald *et al.*, 1992; Erwinsyah, 2008). In general, there is a high potential for density grading as the relationship between vascular bundle-parameters (location in the trunk) is good which has been also observed in our study (further explained in section 5.5).

Vascular bundle percentage is a much better indicator of wood properties (Fathi, 2014). Inspite of an attempt to describe vascular bundle percentage by Fathi (2014), the work had a greater constraint in accessing the samples across different age groups; with sufficient samples across age groups and climatic zones was our advantage. The vascular bundle percentage was significant across age

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groups and radial positions (Table 12). There was an increase in vascular bundle percentage from core to dermal across age groups with over mature palm wood having the maximum percentage of the vascular bundle. This can be attributed to sclerosis occurring as the tree ages. Using vascular bundle percentage as an indicator of wood properties which is highly useful because of better correlation with different wood property parameters.

5.3.2. Fibre morphology

According to Gibson (2012), the concentration of vascualar budles as well as the concentration of fibers within the vascular bundle is greater at the outer zone of the trunk than in the inner zone. The secondary growth mechanism in fibre is responsible for the stiffness and density in palm wood (Bhat *et al.*, 1990). Hence, attempts were made to quantify the fibre morphological parameters such as fibre length, fibre lumen diameter and fibre wall thickness. Sudo (1980) reported that the fibre wall thickness usually decreases from dermal to core wood. The fibre area which is a better representation of fibre diameter usually tends to decrease from dermal to the core (Meylan, 1978). Other works on fibre anatomy helps us to understand the distribution and function of fibres in a qualitative aspect (Parthasarthy and Klootz, 1976a; Weisberg, 1983 and Zimmermann, 1983). The fibre length and diameter was significant across radial position and did not vary significantly due to age or agro-climatic zones. The peculiarity with fibre length and fibre diameter is that both being negatively correlated; fibre length increases from dermal to core wood and vice versa for fibre diameter.

Generally, fibre wall thickness and fibre lumen diameter are inversely proportional and same sort of relation can be interpreted from Table 15 and 16. Also the fibre wall thickness tend to increase from dermal to the core and a reverse trend is seen for fibre lumen diameter helps to conclude that the findings are correct.

5.3.3. Vessel characters

Among the sap conducting elements, vessels along with vascular bundles occupies very less proportion in comparison to dicotyledons (FAO, 1985). Recent literature dealing with coconut palm vessel parameters is lacking. Only few grey literature (Meniado and Lopel, 1977; Tamolang, 1976; Tomlinson, 1961) dealing with vessel dimension are available. In the scenario of wood treatment, a better understating on the vessel characters can play an important role. Table 17 shows the variation in vessel diameter across agro-climatic zones, age groups and radial positions. All the same, vessel lumen diameter was not significant across agro-climatic zones and age groups. Tomlinson (1990) describes that the vessel lumen diameter is high in young stages where parenchyma is also young. As the palm grows in age sclerosis of parenchyma cells occurs, which a significant influence on the vessel lumen diameter (Sudo, 1980). This is obvious in present study also (Figure 17). The maximum vessel lumen diameter of 54. 46 μm, 227.38 μm and 237.16 μm occur in core wood position of young palms (15 - 25 years) in all agro-climatic zones. Further studies on the vessel dimension in relation to the preservative treatment can provide us a better understanding.

5.4. Mechanical properties

The mechanical properties of wood describe the resistance to exterior forces, which cause deformation to the wood. The resistance of wood to such forces depends on their magnitude and the manner of loading (Erwinsyah, 2008). According to Bowyer *et al.* (2003), mechanical properties are usually the most important characteristics of the wood product to be used in structural applications. A structural application is any use for which strength is one of the primary criteria for selection of the material.

The concentric lignification of fibres with increases in age lead to significant variation in mechanical properties of palm wood which in certain cases perform better than conventional wood (Rich, 1987; Tomlinson, 2006). As density is usually considered as a parameter for utilisation the study was framed in accordance with it (Anoop *et al.*, 2011). Hence, dermal wood of mature and over mature palm whose density above 650 kg m^{-3} were selected for assessing the mechanical properties. The intention was to indirectly determine the variation within higher density coconut palm wood. Some fundamental mechanical test such as static bending, compression parallel to grain, compression perpendicular to grain, tensile strength perpendicular to grain, tensile strength parallel to grain, shear and hardness test were conducted. The results of all mechanical tests were not significant across age groups and agro-climatic zones except for compression parallel to grain. Specifically, maximum load and compressive stress at maximum load were significant. This may be attributed to the variation in fiber wall thickness as well as fibre lumen diameter which is significant across the age groups.

Comprehensive mechanical tests have been conducted by Gnanaharan and Dhamodaran (1989), Okai *et al.* (2004) and Hopewell *et al.* (2010). However, all the three works were mostly confined to compression parallel to grain and static bending test, wherein, average strength properties reported were usually expressed in N mm^{-2}. In order to have a better comparison, results obtained from these studies were converted into kg cm^{-2} (Appendix II).

Gnanaharan and Dhamodharan (1989) compared the modulus of elsticity, modulus of rupture and maximum crushing strength of some of the commercial timbers with that of coconut palm wood of age 70-75 years and concluded that the wood properties were on par with that of over mature coconut palm wood. The MOR and MOE in Table 18 and 19 were compared with that of Gnanaharan and Dhamodharan (1989) which reveals that the maximum MOE for over mature (55-65 years) and mature (35-45 years) was 10705.63 N mm^{-2} (109167 kg cm^{-2}) and 9438.42 N mm^{-2} (96245.14 kg cm^{-2}) respectively, which is lower than 15900 N mm^{-2} for 70-75 years aged coconut palm wood. Likewise, the maximum MOR for over mature (55-65 years) and mature (35-45 years) was 105.88 N mm^{-2} (1079.73 kg cm^{-2}) and 88.05 N mm^{-2} (897.87 kg cm^{-2}) respectively, which is more or less on par with 93 N mm^{-2} for 70-75 years aged coconut palm wood

It can be clearly understood that over mature palm wood has better properties suited for utilisation. However, the other part of the result indicates that there was no significant difference in MOE and MOR between over mature and mature palms. The compression strength parallel to grain is another important mechanical parameter that has been studied by researchers. Table 20 and 21 which list down Maximum Load (ML), Compressive Stress at Maximum Load (CS at ML),

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Compressive Stress at Limit of Proportionality (CS at LP) and Modulus of Elasticity (MOE). Among all these parameters ML and CS at ML were significant between age groups indicating that over mature palms have better properties compared to mature palm.

In this back drop, over mature palms have a better prospect in utilisation with respect to strength properties both perpendicular and parallel direction to the axis of the trunk. However, the mature palms (35-45 years) may not perform better than over mature palms in the parallel axis, where due consideration must be taken. This significant difference in CS at ML and ML may also due to the age grouping took for the present study. The mature age group includes palms from 35-45 years, where samples around 35-40 years may be relatively younger compared to the other half (40-45 years) during which the growth and yield of coconut palm subsides slowly. So, future studies may consider age groups with a smaller interval.

Since studies comparing mechanical properties across age group is scarce, further comparison and justification was limited to a greater extent. Other mechanical properties such as compression strength perpendicular to grain (Table 22 and 23), hardness test (Table 24 and 25), shear strength (Table 26 and 27) and tensile strength parallel to grain and perpendicular to grain (Table 28 to 31) are being reported for first time in the Indian context. As one of the objectives was to profile wood properties, these above tests were carried out. Using this information generated from this study, future studies on the wood property of coconut palm wood can be carried out.

5.5. Interrelationship between wood properties

The wholesome relationship between physical, mechanical and anatomical wood properties of coconut palm were not studied previously. Even though there are some significant works intended to understand the relationship between density and anatomical properties (Sudo, 1980), density and other physical properties (Killmann, 1983) and mechanical properties with vascular bundle characters (Fathi, 2014). The present work is a first of its kind to elicit an overall picture of the interrelationship between various wood properties (Table 32 and 33).

Table 32 gives the correlation coefficient for the interrelationship between some of the important palm wood physical properties. Most of the properties have reasonably higher significant correlation coefficients. Density is related to the number of vascular bundles in radial positions and to fiber wall thickness. Since the fiber-cells become laminated and sclerotized with age and the cell wall thickness of the fibers is increased, the zone of the highest density is located in the lower outer zone of the palm stem (Khozirah *et al.*, 1991). The present study also agree with the above work with basic density being highly positively correlated with vascular bundle frequency, vascular bundle percentage and fibre morphological parameters except that of moisture content and fibre length were negatively correlated. Moisture content was usually negatively correlated with many of the physical parameters such as density, vascular bundle frequency, vascular bundle percentage, fibre diameter and fire wall thickness.

Table 33 gives the summary of correlation coefficients of mechanical properties and anatomical properties. No literature was found to confirm many of these findings. However, as observed by many of the researchers basic density was significantly correlated with many of the strength properties including hardness (sides). The reason for the density of coconut palm wood being highly correlated with important mechanical properties is due to the relationship between density and vascular bundle area and vascular bundle percentage which decides the mechanical properties (Fathi, 2014). Further works support the finding that density influences the strength properties in members of palmaceae (Limaye, 1952; Sekhar *et al.*, 1962; Panshin and De Zeeuw, 1970; Killmann and Lim, 1985).

A knowledge of these interrelationships, will help to model the relationship between density and mechanical properties of coconut wood. These models can then be used for grading lumber and for developing sawing patterns for lumber processing.

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SUMMARY

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VI. SUMMARY

Coconut palm stem has a number of features that make it unique as an alternate wood source. The present study has been conducted to profile physical, anatomical and mechanical properties of coconut palm wood of three different age groups (young (15-25 years), mature (35-45 years) and over mature (55-65 years)) grown in three different agro-climatic zones (Malayoram, Central midland and Coastal sandy) of Thrissur district, Kerala.

The salient findings of the study are as follows

1. Dermal wood to core wood ratio calculated in different age groups which indicated that the age is the key deciding factor and more than 80 % is of the basal stem was constituted by dermal part in over mature coconut palms.

2. The density of coconut palm wood varied significantly along the radial direction and the density is greatly influenced by age rather than agro-climatic zones. Density of palm wood ranged from 111.87 kg m^{-3} to 890.61 kg m^{-3}. The basic density tends to increase from core to dermal position and also for young to over mature palms.

3. Moisture content of the coconut palm wood varied from 34.69 % to 401.90 % and the variation was only influenced by radial position of wood in the trunk. Therefore, proper seasoning schedules must be developed. Moisture content was negatively correlated with basic density i.e., moisture content decreased with increasing density.

4. Volumetric shrinkage of palms was not significantly influenced by age of the palm and agro-climatic zone. Volumetric shrinkage reaches up to 33.05 % where palm wood tends to collapse.

5. Vascular bundle frequency was significantly influenced by position within the trunk. Vascular bundle frequency showed an increasing trend from core to dermal position. The vascular bundle diameter and sheath thickness also showed the same trend of variation along the radial position but not influenced by age or agro-climatic zones.

6. Vascular bundle percentage was significantly influenced by age of the palm and position in the trunk. Dermal wood of over mature palms contained 78.15 % of vascular bundles in one square centimeter and it decreased towards the core. Also, the percentage decreases with decreasing age.

7. Fibre length and fibre diameter was not influenced by age and agro-climatic zones. Fibre length increases from dermal wood (1687.35 μm) to core wood (2812.93 μm). Fibre diameter ranged from 32.26 μm to 53.84 μm.

8. Fibre wall thickness and fibre lumen diameter were related to each other on equating to fibre diameter. Both the parameters were significantly different among the age groups and radial position. Fibre wall thickness ranged from 7.42 μm to 20.98 μm.

9. Mechanical properties were estimated for palm wood having density more than 650 kg m^{-3}. All the mechanical properties studied did not vary significantly across age groups and agro-climatic zones which signifies that high-density wood (above 650 kg m^{-3}) can be used for all structural purpose, since there was no difference in the mechanical properties of wood from mature and over mature palms.

10. Since, basic density being highly positively correlated with mechanical properties, estimation of density can be used as a key to determine end use in field condition as well as in the industrial level.

11. Vascular bundle frequency was highly correlated with the basic density. Determination of vascular bundle frequency may also indirectly aid in determining the end use.

12. Other mechanical properties such as hardness, compressive stress, shear stress and tensile strength have been completely profiled as a base line data for coconut palm of two age groups (34-45 years (mature) and 55-65 years (over mature)) from three agro-climatic zones (Malayoram, Central midland and Coastal sandy).

13. Mechanical properties maximed to 1079.73 kg cm^{-2} for modulus of rupture, 109167.87 kg cm^{-2} modulus of elasticity, 717.71 kg cm^{-2} for compressive stress, 985.85 kg cm^{-2} for hardness at side, 113.71 kg cm^{-2} for maximum shear stress, 18.52 kg cm^{-2} for maximum tensile strength perpendicular to grain and 778.48 kg cm^{-2} for maximum tensile strength parallel to grain.

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VII. REFERENCES

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WOOD PROPERTY PROFILING OF COCONUT PALMS GROWN IN DIFFERENT AGRO-CLIMATIC ZONES OF THRISSUR DISTRICT, KERALA

by

ALEX. K. GEORGE

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ABSTRACT OF THE THESIS

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ABSTRACT

Wood anatomical, physical and mechanical properties of samples collected from 51 coconut palms belonging to three age groups viz., 15-25 years (young), 35-45 years (mature) and 55-65 years (over mature), grown in three agro-climatic zones (Malayoram, Central midland and Coastal sandy) of Thrissur district, Kerala were profiled in this study.

Dermal, sub-dermal and core wood from each sample were used for assessing physical and anatomical properties and samples of density above 650 kg m^{-3} were selected for profiling mechanical properties. Nested analysis of variance was carried out to analyse the variation in coconut palm wood properties due to location, age and radial position.

Most of the physical, anatomical and mechanical properties did not vary significantly across agro-climatic zones and age groups. However, across age groups, basic density, vascular bundle percentage, fibre lumen diameter, fibre wall thickness and compression parallel to grain (maximum load and compressive stress at maximum load) were found to vary significantly.

Along the radial positions there was significant difference in physical and anatomical properties. Basic density, being highly positively correlated with mechanical and anatomical properties, estimation of density can be used as a key to determine end use under field conditions for potential utilization at the industrial level.

APPENDICES`

APPENDIX I

1. Summary of ANOVA

1.1. Basic density (kg m^{-3}) versus zones, age, part

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	27835	13918	0.02	0.978
age(zones)	6	4157683	692947	2.70	0.048
part(zones, age)	18	4618315	256573	94.47	0.000
Error	126	342201	2716		
Total	152	9146034			

1.2. Oven dry density (kg m^{-3}) versus zones, age, part

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	11774	5887	0.01	0.991
age(zones)	6	4070998	678500	2.23	0.088
part(zones, age)	18	5487018	304834	63.70	0.000
Error	126	602994	4786		
Total	152	10172784			

1.3. Vascular bundle frequency (cm^{-2}) versus zones, age, part

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	48.1	24.06	0.04	0.966
age(zones)	6	4434.2	739.04	0.37	0.891
part(zones, age)	18	36351.1	2019.51	19.93	0.000
Error	126	12765.9	101.32		
Total	152	53599.4			

1.4. Moisture content (%) versus zones, age, part

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	36989	18494	0.24	0.793
age(zones)	6	502319	83720	2.18	0.094
part(zones, age)	18	691424	38412	14.56	0.000
Error	126	332431	2638		
Total	152	1563162			

1.5. Vascular bundle sheath thickness (µm) versus zones, age, part

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	276224	138112	1.35	0.324
age(zones)	6	652790	108798	0.71	0.648
part(zones, age)	18	2769598	153867	5.12	0.000
Error	126	3785720	30045		
Total	152	7484332			

1.6. Vascular bundle diameter (μm) versus zones, age, part

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	116818	58409	0.35	0.717
age(zones)	6	1077927	179655	1.72	0.174
part(zones, age)	18	1882449	104580	3.79	0.000
Error	126	3473273	27566		
Total	152	6550467			

1.7. Vascular bundle percentage versus zones, age, part

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	1012	506.2	0.23	0.802
age(zones)	6	14441	2406.8	2.83	0.041
part(zones, age)	18	15321	851.2	6.04	0.000
Error	126	17766	141.0		
Total	152	48540			

1.8. Vessel lumen diameter (μm) versus zones, age, part

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	103.1	51.534	2.08	0.202
age(zones)	6	158.0	26.341	1.08	0.412
part(zones, age)	18	440.1	24.448	2.88	0.000
Error	126	1070.1	8.493		
Total	152	1771.3			

1.9. Fibre length (μm) versus zones, age, part

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	165083	82541	0.33	0.732
age(zones)	6	1631672	271945	0.69	0.662
part(zones, age)	18	7114084	395227	12.36	0.000
Error	126	4028255	31970		
Total	152	12939094			

1.10. Fibre diameter (μm) versus zones, age, part

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	699.9	349.95	1.48	0.299
age(zones)	6	1539.6	256.60	1.84	0.147
part(zones, age)	18	2509.7	139.43	6.67	0.000
Error	126	2635.6	20.92		
Total	152	7384.8			

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1.11. Fibre lumen diameter (μm) versus zones, age, part

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	94.08	47.039	0.17	0.847
age(zones)	6	1806.52	301.087	4.94	0.004
part(zones, age)	18	1097.55	60.975	6.84	0.000
Error	126	1123.12	8.914		
Total	152	4121.27			

1.12. Fibre wall thickness (μm) versus zones, age, part

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	301.2	150.600	0.60	0.577
age(zones)	6	1636.3	272.716	3.04	0.031
part(zones, age)	18	1614.9	89.718	15.63	0.000
Error	126	723.1	5.739		
Total	152	4275.5			

1.13. Longitudinal shrinkage (%) versus zones, age, part

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	8.202	4.101	2.13	0.193
age(zones)	6	11.999	2.000	1.01	0.447
part(zones, age)	18	35.490	1.972	1.72	0.045
Error	126	144.809	1.149		
Total	152	200.499			

1.14. Radial and Tangential shrinkage (%) versus zones, age, part

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	41.57	20.78	1.62	0.259
age(zones)	6	74.74	12.46	0.29	0.933
part(zones, age)	18	767.77	42.65	2.52	0.001
Error	126	2136.42	16.96		
Total	152	3020.49			

1.15. Volumetric shrinkage (%) versus zones, age, part

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	495.2	247.58	1.09	0.394
age(zones)	6	1470.1	245.02	1.79	0.157
part(zones, age)	18	2460.1	136.67	3.18	0.000
Error	126	5419.0	43.01		
Total	152	9844.4			

1.16. Maximum load (kg) - shear versus zones, age

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	2641217	1320608	1.73	0.305
age(zones)	3	2294053	764684	1.10	0.374
Error	20	13961132	698057		
Total	25	18401249			

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1.17. MSS (kg cm^{-2}) - shear versus zones, age

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	4226	2113	1.73	0.305
age(zones)	3	3671	1224	1.10	0.374
Error	20	22339	1117		
Total	25	29443			

1.18. MOR (kg cm^{-2}) - Static bending versus zones, age

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	20965	10482	0.14	0.873
age(zones)	3	225639	75213	1.41	0.268
Error	20	1063717	53186		
Total	25	1305463			

1.19. ML (kg) - Static bending versus zones, age

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	1073	536.4	0.26	0.783 x
age(zones)	3	6168	2055.9	1.25	0.320
Error	20	33003	1650.2		
Total	25	40078			

1.20. HSS at ML (kg cm^{-2}) - Static bending versus zones, age

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	31.95	15.98	0.19	0.838
age(zones)	3	260.29	86.76	1.34	0.288
Error	20	1290.51	64.53		
Total	25	1576.52			

1.21. HSS at LP (kg cm^{-2}) - Static bending versus zones, age

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	55.42	27.71	0.47	0.661
age(zones)	3	177.93	59.31	1.11	0.369
Error	20	1069.19	53.46		
Total	25	1275.05			

1.22. FS at LP (kg cm^{-2}) - Static bending versus zones, age

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	43914	21957	0.43	0.680
age(zones)	3	152725	50908	1.17	0.348
Error	20	873753	43688		
Total	25	1047900			

1.23. MOE (kg cm^{-2}) - Static bending versus zones, age

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	405165043	202582522	0.23	0.807
age(zones)	3	2716043201	905347734	2.21	0.118
Error	20	8187863456	409393173		
Total	25	11097805543			

1.24. ML (kg) - Compression parallel to grain versus zones, age

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	536322	268161	0.34	0.738
age(zones)	3	2481898	827299	3.18	0.047
Error	20	5210232	260512		
Total	25	7986153			

1.25. CS at LP (kg cm^{-2}) - Compression parallel to grain versus zones, age

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	61908	30954	1.69	0.315
age(zones)	3	55982	18661	1.61	0.219
Error	20	232158	11608		
Total	25	336991			

1.26. CS at ML (kg cm^{-2}) - Compression parallel to grain versus zones, age

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	36431	18216	0.31	0.757
age(zones)	3	185747	61916	3.27	0.042
Error	20	378286	18914		
Total	25	583213			

1.27. MOE (kg cm^{-2}) - Compression parallel to grain versus zones, age

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	915330563	457665282	2.58	0.216
age(zones)	3	546039873	182013291	1.92	0.159
Error	20	1895302702	94765135		
Total	25	3189408851			

1.28. CS at LP (kg cm^{-2}) - Compression perpendicular versus zones, age

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	41062	20531	4.17	0.123
age(zones)	3	14703	4901	0.93	0.443
Error	20	105144	5257		
Total	25	155444			

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1.29. CS at 2.5 mm deflection (kg cm^{-2}) - Compression perpendicular to grain versus zones, age

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	85083	42542	2.01	0.271
age(zones)	3	64671	21557	1.45	0.258
Error	20	296985	14849		
Total	25	426962			

1.30. MOE (kg cm^{-2}) - Compression perpendicular to grain versus zones, age

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	419647053	209823527	4.60	0.100
age(zones)	3	130008454	43336151	0.50	0.686
Error	20	1728955055	86447753		
Total	25	2221009982			

1.31. ML(kg) - Tensile perpendicular to grain versus zones, age

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	8725	4362	2.79	0.178
age(zones)	3	4359	1453	0.41	0.750
Error	20	71587	3579		
Total	25	89343			

1.32. MTS (kg cm^{-2}) - Tensile perpendicular to grain versus zones, age

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	98.81	49.41	2.84	0.176
age(zones)	3	48.82	16.27	0.43	0.732
Error	20	753.26	37.66		
Total	25	953.93			

1.33. ML (kg) - Tensile parallel to grain versus zones, age

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	6604	3302	0.09	0.918
age(zones)	3	115950	38650	1.95	0.153
Error	20	395426	19771		
Total	25	532497			

1.34. TS at ML (kg cm^{-2}) - Tensile parallel to grain versus zones, age

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	11986	5993	0.05	0.954
age(zones)	3	387819	129273	1.88	0.166
Error	20	1375834	68792		
Total	25	1821206			

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1.35. Side (kg) - hardness versus zones, age

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	486569	243285	4.22	0.114
age(zones)	3	166585	55528	0.58	0.636
Error	20	1921237	96062		
Total	25	2541773			

1.36. End (kg) - hardness versus zones, age

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	132333	66166	2.99	0.158
age(zones)	3	59558	19853	0.31	0.819
Error	20	1289125	64456		
Total	25	1460743			

1.37. Volume of palms versus zones, age

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	0.03176	0.015878	0.84	0.475
age(zones)	6	0.12080	0.020133	3.30	0.009
Error	42	0.25603	0.006096		
Total	50	0.40858			

1.38. Dermal to core wood ratio versus zones, age

Source	DF	Adj SS	Adj MS	F-Value	P-Value
zones	2	11.43	5.717	0.14	0.869
age(zones)	6	257.84	42.974	5.51	0.000
Error	42	327.59	7.800		
Total	50	596.87			

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Appendix II

Conversion factor

$1\ kg\ cm^{-2} = 0.0980665\ Nmm^{-2}$

MOE (Modulus of Elasticity), MOR (Modulus of Rupture) and Compression parallel to grain of different structural properties in air dry condition. (Gnanaharan and Dhamodaran, 1989)

Species	Static bending		Compression parallel to grain MCS (Nmm^{-2})	Static bending		Compression parallel to grain MCS ($kgcm^{-2}$)
	MOR (Nmm^{-2})	MOE (Nmm^{-2})		MOR ($kgcm^{-2}$)	MOE ($kgcm^{-2}$)	
Albizia odoratissima	144	14500	79	14.122	1421.964	7.747
Artocarpus heterophyllus	81	10100	50	7.943	990.472	4.903
A. hirsutus	97	12200	62	9.512	1196.411	6.080
Tectona grandis	96	12000	53	9.414	1176.798	5.198
Terminalia paniculata	112	14300	64	10.983	1402.351	6.276
Xylia xylocarpa	110	14200	71	10.787	1392.544	6.963
Cocos nucifera (over-mature)	93	15900	57	9.120	1559.257	5.590