Structural and mechanical properties of the wood from coconut palms, oil palms and date palms

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Leila Fathi
aus Bandar-e Anzali, Iran

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Susan J. Ortloff ________________________ May 12, 2014

Susan J. Ortloff

1305 SW 9th Street
Dundee, OR 97115, USA

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der Fakultät für Mathematik, Informatik und Naturwissenschaften

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Weiterer Gutachter der Dissertation:

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I dedicated this dissertation

To both my beloved parents

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Whose prayers support and love blessed my heart and sustained me in the years of life

My brothers

Rahman, Arman and Mehran

My beloved husband

Mohsen Bahmani

Structural and mechanical properties of the wood from coconut palms, oil palms and date palms

Summary

Palm trees are a family (Arecaceae) of plants with hundreds of species. Economically most important species are coconut palm (Cocos nucifera), oil palm (Elaeis guineensis) and date palm (Phoenix dactylifera). With the exception of coconut palm wood from palm trees has not been used to a large extend but is available at large volume. According to FAO today oil-, coconut- and date palms cover some 30 million ha with a total stem wood potential of 150-200 million m³ per year. Especially for oil palms planted on 20 million ha today, it is estimated to increase the area and the stem wood volume remarkably during the next years. Generally this wood resource can play an important role in the regional/worldwide wood supply; mainly in Asia, Arabic countries, Africa and Latin America. The stem of the tree (coconut, oil and date palm) is between 10 and 20 (25) m long, has a base diameter of 40-60 cm and a taper of 0.3-0.7 cm/m. Being monocotyledons palms show distinct differences of the wood structure compared to common wood species. No radial growth of the stem and mainly consisting of parenchyma cells and vascular bundles (VB) result in distinct variation of density and mechanical properties.

In a comprehensive PhD project, material from Mexico and Indonesia (coco-wood), Thailand (oil palm) and Iran (date palm) was investigated for structure and technical properties in trunk sections/zones peripheral to the inner zone and along the trunk height. The inter-relationships of the different physical and mechanical properties and in relation to the anatomical characteristics were analyzed. In addition the individual properties of the VB, being the reinforcement elements of palm wood were investigated.

Anatomical, physical and mechanical properties of Mexican and Indonesian coconut palm, Thailand oil palm and Iranian date palm were tested in wide range of laboratory research such as frequency, diameter, area, cross cut area and density of VB and parenchyma (Indonesian coconut wood), lignification and cell structure (Mexican coconut wood), ultimate tensile strength and modulus of elasticity of VB, compression strengths (parallel to grain) of wood, the tensile strength (parallel and perpendicular to grain) (Indonesian coconut wood) and shear parallel to grain (Indonesian coconut wood).

The results indicated that the density and mechanical properties of coconut and oil palm wood are closely related to the anatomical characteristics. All properties (density of

wood, frequency of vascular bundles and mechanical properties) increase with the radial distance from the inner to the outer zone of the trunk. The properties density and strength also decrease from the bottom to the top of the trunk. These differences are correlated with the share of VB bundles of the wood volume (volume fraction of VB). In the outer zones vascular bundles are more frequent and bigger in diameter than in the inner zones (especially at trunk bottom). At the top of the trunk, although density and mechanical properties are lower compared to the trunk bottom, the volume fraction of VB –and even more the number- is signficantly higher. But the density of VB at the trunk top is significantly lower compared to trunk base because of (a) the smaller diameter of VB resulting in (b) reduced area fraction of the fiber caps of the VB (vessel area remains almost constant) and (c) thinner fiber cell walls due to younger age of the cells and caused by less additional cell wall layers (secondary growth).

Because density and strength of coconut and oil palm timber is highly correlated with the position within the stem, density and stiffness, any one of these two factors (the best is location+ density) can be used as a basis for grading the timber into different strength classes.

For coconut and oil palm the relationships between the grading indicating properties are at high statistical level whereas with oil palm timber a close correlation exits only across the trunk diameter (at all height levels of the trunk) but not along the trunk. For a good grading an indication is required from what trunk height level (base, middle and top of trunk) the timber was processed.

The characteristics and properties obtained are comparable with literature and material investigated from other parts of the world. The density for coconut ranged from low to high density with 0.41-1.11 g/cm^3. The compression strength, tensile strength and shear strength ranged from weak to very strong due to the density variation.

Results for date palm are very much different; there is no significant variation or gradient in density from inner to peripheral zones, also not from base to top. The values for compression strength and the modulus of elasticity in the central zone of the trunk are higher than for the peripheral and inner zones of the trunk.

Using the results of these basic studies it is possible to develop a mechanical model of palm wood (different for the three palm species) in order to explain most mechanical properties from the structure and density of the wood. Such a model is also necessary or at least helpful for the development of timber lumber grading strategies and methods. A timber/lumber simple material model which is then further refined by specific testing and statistical analysis could serve as basis for the development of design values for load-bearing construction and for risk analysis as well.

Strukturelle und mechanische Eigenschaften des Holzes von Kokospalmen, Ölpalmen und Dattelpalmen

Kurzfassung

Die botanische Familie Palmen (Arecaceae) umfasst hunderte von Arten. Die wirtschaftlich wichtigsten sind Kokospalme (Cocos nucifera, KP), Ölpalme (Elaeis guineensis, ÖP) und Dattelpalme (Phoenix dactylifera, DP). Nach Angaben der FAO umfassen die plantagenmäßigen Anbauflächen dieser drei Palmenarten derzeit etwa 30 Millionen ha weltweit mit einem potentiellen Nutzungspotential an Stammholz von 150-200 Millionen m^3 pro Jahr. Ölpalmen stehen derzeit auf ca. 20 Millionen ha, es wird geschätzt, dass diese Fläche und damit das Stammholzpotential sich in den nächsten Jahren erheblich erhöhen werden. Grundsätzlich kann Ölpalmholz eine wichtige Rolle in der regionalen und globalen Holzversorgung spielen, vor allem in Asien (ÖP, KP), Mittel- und Südamerika (KP, ÖP), Westafrika (ÖP) und im Arabischen Raum (DP).

Der Stamm der drei Palmenarten ist zwischen 10 m und 20 m (25 m) lang, am Stammfuß ca. 40 cm bis 60 cm im Durchmesser mit einer Abholzigkeit von 0.3-0.7 cm/m. Als Monocotylidonen sind Palmen in ihrer Holzstruktur deutlich unterschiedlich zu den „normalen Holzarten“ aufgebaut. Kein Dickenwachstum des Stammes sondern Holzgewebe aus einem Grundparenchym (Matrix) und Leitbündel ergeben erhebliche Dichteunterschiede und erhebliche Unterschiede der mechanischen Eigenschaften innerhalb eines Stammes.

In einem umfassenden Projekt wurden Struktur und technische Eigenschaften des Holzes aus unterschiedlichen Bereichen ("Zonen" entlang des Stammdurchmessers und über die Stammlänge) untersucht. Das Untersuchungsmaterial stammte aus Mexico und Indonesien (KP), Thailand (ÖP) und dem Iran (DP).Die Zusammenhänge zwischen physikalischen und mechanischen Holzeigenschaften sowie zwischen Strukturelementen und den physikalisch-mechanischen Eigenschaften wurden ermittelt. Zusätzlich wurden relevante Eigenschaften der Leitbündel wie Anzahl, Größe, Dichte und Zugfestigkeit untersucht.

Die wesentlichen experimentell untersuchten Holzeigenschaften waren:

a) Leitbündel:
   Anzahl, Häufigkeit, Durchmesser, Querschnittsform und Querschnittsfläche, Dichte, Lignifizierung, Zugfestigkeit, Zug-Elastizitätsmodul
b) Parenchym:
   Anteil am Holzvolumen, Dichte (berechnet)

c) Holz:

Dichte, Dichteverteilung im Stamm, Druckfestigkeit, Zugfestigkeit längs und quer (nur KP Indonesien), Druck-Elastizitätsmodul, Scherfestigkeit (nur KP Indonesien).

Die Ergebnisse zeigen, dass die Dichte und die mechanischen Holzeigenschaften eng mit den Strukturmerkmalen korreliert sind. Für Kokospalmen und Ölpalmen nehmen alle wichtigen Eigenschaften im Stamm von außen nach innen und von unten nach oben hin ab. Deutlich ausgeprägt ist dies für die Dichte und die Festigkeiten. Beides ist korreliert mit dem Anteil der Leitbündel am Holzgewebe (Volumenanteil). Im äußeren Stammbereich sind mehr Leitbündel vorhanden und sie sind größer (Durchmesser, Volumenanteil) als im Stamminneren. Deutlich ausgeprägt ist das im unteren Stammbereich. Obwohl im oberen Stammbereich die Dichte und die mechanischen Eigenschaften deutlich geringer sind als am Stammfuß sind die Anzahl der Leitbündel je Flächeneinheit und ihr Volumenanteil oft höher als am Stammfuß. Allerdings ist die Dichte der Leitbündel oben deutlich geringer als unten im Stamm weil (a) die Durchmesser der Leitbündel kleiner sind, was (b) sich in einem geringerem Flächen-/Volumenanteil der Faserkappen um die Gefäße (Gefäßfläche annähern gleichbleibend) auswirkt und (c) die Zellwände der Fasern dünner sind, weil sie als junge Zellen weit weniger zusätzliche Wandschichten aufgelagert haben (sekundäres Wachstum). Da Dichte und mechanische Eigenschaften eng miteinander und jeweils eng mit der Lage im Stamm korreliert sind, kann jede dieser Eigenschaften (am besten Dichte und Lage im Stamm) als Basis für eine Festigkeitsorientierung des Holzes von Kokospalme und Ölpalme genutzt werden. Ähnlich gute Ergebnisse lassen sich aus dem Flächenanteil der Leitbündel und der Lage des zu sortierenden Holzes im Stamm erreichen.

Während für Kokos- und Ölpalme die statistischen Zusammenhänge Struktur-Lage im Stamm-Dichte-Festigkeit recht gut sind, ist dieses für Dattelpalme nicht der Fall. Ein noch relativ guter Zusammenhang ergibt sich für Dichte und Festigkeiten über den Stammdurchmesser für alle Stammhöhen separat, aber ein solcher/ähnlicher Zusammenhang ergibt sich nicht für die Stammhöhe. Um trennscharf sortieren zu können ist die Kenntnis der Herkunft/Lage im Stamm unbedingt erforderlich.

Grundsätzlich waren die Eigenschaften von Kokosholz aus Indonesien etwas höher als die des Holzes aus Mexico (siehe auch Guzman 1989) und schwankten (Indonesien) für die Dichte zwischen 0.41 und 1.11 g/cm^3. Entsprechend ergab sich eine breite Spanne der Festigkeits- und elastischen Eigenschaften. Die Werte für Ölpalme liegen deutlich unter denen von Kokospalmen (Dichte zwischen 0.30 und 0.59 g/cm^3), entsprechend liegen auch die mechanischen Eigenschaften niedriger; sie folgen aber ähnlichen Verteilungsmustern innerhalb des Stammes. Für Dattelpalme ergibt sich ein gänzlich anderes Bild: die ermittelten Elastizitäten und Festigkeiten waren in der Übergangszone (central) zwischen äußerer und innerer Zone (peripheral, inner zone) am höchsten; die Dichte ist über den Querschnitt des Stammes wenig unterschiedlich.

Mit den gefundenen Untersuchungsergebnissen und den ermittelten statistischen Zusammenhängen lässt sich für das Holz jeder der drei Palmenarten ein mathematisch-mechanisches Modell entwickeln, das die meisten der Eigenschaften in ihrer Größe und ihrer Variation aus den Grundparametern heraus beschreiben kann. Ein Material-Modell ist erforderlich oder zumindest hilfreich für die Entwicklung von Sortierstrategien und –verfahren für eine Dichte- oder Festigkeitssortierung. Ein solches Modell könnte auch durch zusätzliche experimentelle und statistische Untersuchungen weiterentwickelt werden für die grundlegende Ermittlung von Rechenwerten für eine statistische Bemessung von Tragwerten und Bauelementen sowie für eine Risikoabschätzung für Last-tragende Konstruktionen.

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1. Introduction

1.1 Information on palm trees

Palm trees are a family of plants (Arecaceae). Most of them are trees but some are shrubs. Most species grow in tropical regions but some in subtropical or semi-arid regions like date palms. Economically important palm species are: coconut palm, oil palm, date palm. Palms are one of the widely planted tree species. They have been important to humans throughout the history. Palms are used for food, animal feed and many other everyday products and commonly found in parks and gardens.

A palm tree is divided into roots, trunk and crown. The structure of palms is simple compared to most trees. Palms do not have a bark. Instead, the epidermis hardens to form a protective layer. The trunk consists of a ground parenchymatous tissue and embedded vascular bundles. 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 (Jones 1995).

Due to the absence of a cambium, palm trees have no secondary growth. The increase in diameter is limited and caused by cell division and cell enlargement in the parenchymatous ground tissue as well as in the enlargement of vascular bundles (Killmann 1993; Franke 1994; Jones 1995).

Corley and Tinker (2003) described the structure of vascular bundles. The orientation of vascular bundles within the trunk is not straight. With increasing height the 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 amount of vascular bundles is higher in the peripheral zone and less but more even in the center section. The bundles within the central part of the trunk form a spiral pattern (Corley and Tinker 2003).

The vascular bundles have "fiber caps" of high density which give the wood stability and thus higher mechanical properties. Vascular bundles also consist of vessels which transport water and nutrients. Parenchyma cells are the main matrix tissue. The parenchyma cells are almost full of water as they are the water and extractives storage. Because of the thin cell walls the parenchyma cells have very low mechanical stability. The mixture of high density of fiber caps of above 1 g/cm³ and the parenchyma of 0.1- 0.25 g/cm³ shows a very inhomogeneous and anisotropic behavior although the wood does not exhibit different shrinkage levels in radial and tangential directions. The palm wood does not have wood rays. The vascular bundles do not run parallel with the stem axis; instead they run from the inner stem peripheral to the palm fronts. Warps and bows result during drying caused by vascular bundles that do not grow straight. The cell collapse which occurs when the palm trees are dried is due to the thin cell walls of the parenchyma cells, shown by checks and cracks and higher shrinkage properties (Killmann 1992).

The leaf arises at a point called the node, the area in between is the internode. When the leaves fall they leave a scar where the leaf was attached thus giving the only possible indication about the age of a palm. On some palms they may even show up as a ring. The scars occur at the point of the nodes and are sometimes known as annular rings (Jones 1995).

1.2 Coconut palm (Cocos nucifera)

The coconut palm, Cocos nucifera, grows mainly in Southeast Asia and Central America. The total planted area with coconut palms is some 12 million ha, of which more than 90% grow in Asia (APCC 1998). Major coconut wood producers are Indonesia, the Philippines and India. Today at least 30% of the palms are over mature (>60 years old) which equals about 200-300 mio m³ stocking volume. The long term harvesting potential for coconut palm trunks is at least 15-20 mio m³ per year.

Table 1. Estimated number of coconut palms in Asia and the Pacific, 2006

Country	Coconut area ('000 ha) 2006	Estimated number of coconut palms ('000)[1]	% senile (average)	Total number of senile palms ('000 palms) → equal to m³ I tree = 1 m³
Asia total of which	**9,965**	**996,500**		**347,665**
Indonesia	3,818	381,800	50	190,900
Philippines	3,243	324,300	30[2]	97,290
India	1,935	193,500	20	38,700
Sri Lanka	395	39,500	15	5,925
Thailand	226	22,600	30[2]	6,780
Malaysia	115	11,500	32	3,680
Vietnam	133	13,300	10	1,330
Pacific Islands	**333**	**33,300**		**11,818**
Asia Pacific, total	**10,298**	**1,029,800**		**359,483**

[1] At 100 palms/hectare. Figures based on 2006 data of the FAO study.

[2] Average for Asia Pacific.

More than 80% of the total world production comes from the Asia–Pacific countries (Adkins et al. 2006).

1.2.1 Properties of the coconut palm wood

Although questionable, because it is from monocotyledons, the term "coconut wood" has been established for the material of the coconut palm stem. Unlike conventional trees, palms, like many other monocotyledons, have vascular fiber bundles, seen as a red-brown spots on the cross-section, scattered in a yellowish parenchymatic ground tissue. These bundles with high density and strength contain the water and nutrient transport system of xylem vessels and phloem as well as thick-walled fibers around the large diameter transport elements, all giving the stem and the wood their strength. 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, and thus in a very non-homogenous raw material. The composition of vascular bundles and parenchyma resulted in a typical reinforced material (like steel reinforced concrete). The properties are influenced very much by the reinforcement of vascular bundles. The reinforcement can be described with number, diameter and density of the vascular bundles. Principally, density decreases towards the inner of the stem, and over stem height. Figure 1 gives a qualitative impression of the density distribution over the stem from 80 year old Philippine palms. Figure 2 shows the distribution of the vascular bundles and the density (dark=high density) over cross sections from Mexican coconut wood.

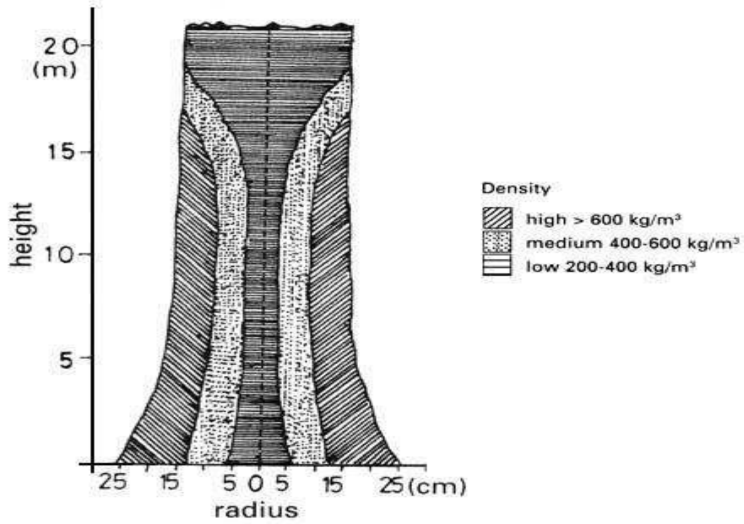


Figure 1. Schematic picture of density distribution in a mature coconut palm stem (from Killmann and Fink 1996)

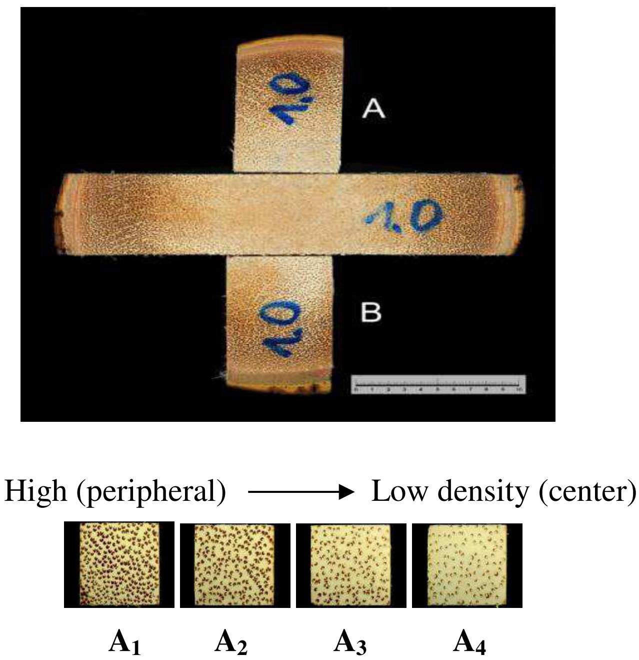


Figure 2. Wood cross sections of a coconut palm stem

The physical properties of coconut wood depend on density, moisture content and shrinkage. Differences in distribution of bundles, proportion of fibers to other cell types in vascular bundles and thickness of fiber and ground parenchyma cell walls are all responsible for variations in wood density (Butterfield and Meylan 1979) and even more the mechanical properties. The density of wood and the concentration of vascular bundles and therefore elasto-mechanic properties per unit area are important properties for visual or mechanical grading (Sulc 1979).

Use of coconut wood

There are a number of products traditionally provided by the coconut palm, like roofing material (from leaves), ropes and strings (coir from husk), beverages (coconut juice), food (coconut, palm heart), fuel (from husks, nuts and dried leaves), and wood (from the stem).The stems are mainly converted into wood products in small scale operations, often in very rough form. The wood is difficult to process because of density variations, high density and ash content. It is used as a substitute for conventional timber in building and bridge construction, but also for tools, toys, simple furniture, fencing and other items of daily life. In some parts of the tropics, e.g. the Maldives, coconut wood has been traditionally used for building fishing boats. Throughout the copra producing regions of the world there is increasing interests in the utilization of wood from over-mature coconut trees (Alston 1976; Killmann and Fink 1996). The performance of coconut wood in industrial uses, construction and housing is closely related to its physical and mechanical properties as well anatomical characteristics.

The physical properties of coconut wood depend on density, moisture content and shrinkage. Density, for example, helps to determine the physical and mechanical properties and characterize different kinds of wood and woody materials for their intended use (Mitchell 1964; Gurfinkel 1973). It is often described that the variability of dry density within a trunk of coconut palm is very distinct, ranging from >1.0 g/cm³ (lower, peripheral zone of the trunk) through 0.4–0.6 (inner zone of the trunk) to <0.35 g/cm³) (upper, inner). This variability requires specific sawing patterns individual in preparing of the trunks in order to achieve boards with small density variation (Frühwald et al. 1992). The main reason for density variation is seen in (1) the number and distribution of vascular bundles, (2) the dimension (diameter) as well as thickness of the cell walls of the bundles and (3) the cell wall thickness of the ground parenchyma. The density of wood and the concentration of vascular bundles per unit area are important properties for visual and mechanical grading procedures (Sulc 1979).

1.3 Oil palm (Elaeis guineensis)

Oil palms (Elaeis guineensis) are one of the most economically important palms. They are planted because of the oil production which is extracted from the fruits. Elaeis guineensis is cultivated on approximately 15 million ha across the world (Fitzherbert et al. 2008; Koh and Ghazoul 2008; Koh and Wilcove 2008a; FAO 2009). The palm oil is used in many food and household products as well as for biodiesel production. Increasing global demand for food and fuel are driving forest clearance in the tropics, a significant portion of which is due to the rapid expansion of oil palm monocropping (UNEP 2011).

After a certain period (25-30 years) the oil palms are felled and replaced by new seedlings. Replacement has to be done because the production of fresh fruit bunches is low or because harvesting becomes too difficult and expensive with increase in height. As in coconut palm, the wood itself is a by-product and until now not being used on a large industrial scale. In most countries it is prohibited to burn the trunks after felling, even though the practice was common until recently. The advantages of the oil palm lumber are that it is cheap, light and available in large amounts. High quality material like lightweight products and insulation, sandwich boards with light cores and low weight products like packaging material as well as plywood and other panels could be made out of palm oil lumber.

Palm oil is an international commodity being used for food as well as household and industrial purposes. As global demand for palm oil is expected to double by 2020, researchers have broadly studied the varying environmental threats arising from increased oil palm production (UNEP 2011).

1.3.1 Properties of oil palm wood

The oil palm (Elaeis Jacq.) consists of two species, the African oil palm (Elaeis guineensis Jacq.) and the American oil palm [Elaeis oleifera (Kunth) Cortés]. Corley and Tinker (2003) reported a third species called Elaeis odora, but they state that it is not being cultivated and little is known about it.

African oil palm

The diameter and height of the stem vary according to the location of the growing site and availability of nutrients (Killmann 1993). Taper is very low due to the absence of secondary growth. In natural stands the oil palm can reach heights of up to 30 m due to competition with surrounding trees and diameters of 25-75 cm. In plantations, the oil palm reaches heights of 12-15 m (Killmann 1993; Franke 1994). This difference is due to the shorter lifespan on plantations where the palms are cut before they are fully grown. Sheil et al. (2009) gave precise numbers by stating that a typical plantation has a spacing of 9.0×7.5 m, which equals 148 palms per hectare and production of one new frond every 3 weeks by every palm. It was further said that each new leaf adds 4.5 cm to the trunk height (80 cm per year=20 m in 25 years) (Killmann 1993; Franke 1994; Sheil et al. 2009).

American oil palm

The growth of the American oil palm is much slower than that of the African oil palm. The stem is also most often procumbent with the young part being erect and the older trunk part lying on the ground or at least prostrate. This feature is useful regarding the reaching of the bunches. For use of the timber that would probably result in difficulties in high deformations during drying because of the twisted and bended vascular bundles. This species is more sensitive to the cold and therefore unsuitable for the subtropics (Jones 1995; Corley and Tinker 2003).

The oil palm trunk can be divided into three parts, the cortex, the peripheral zone and the central zone on the cross section of the trunk (Killmann and Lim 1985). To determine the density, Lim and Khoo (1986) divided the cross section into peripheral-, central- and inner zone (Killmann and Lim 1985; Lim and Khoo 1986; Corley and Tinker 2003).

The cortex is narrow and its thickness is between 27 mm at bottom and 14 mm at top (10 m) (Killmann and Lim 1985). It is largely composed of ground parenchyma with numerous longitudinal fibrous strands which are small without any definite shape (Killmann and Lim 1985; Lim and Khoo 1986).

The periphery contains a narrow layer of parenchyma cells and high density per area of vascular bundles forming a hardened zone which gives the palm the main mechanical support. Boards sawn from this zone are supposed to have the highest density and thus highest mechanical properties (Killmann and Lim 1985).

The central cylinder consists mainly of ground parenchymatous tissues scattered with vascular bundles. About 80% of the trunk total area consists of this zone which is made of slightly larger and widely scattered vascular bundles embedded in the thin-walled parenchymatous ground tissues. The vascular bundles towards the periphery and underneath the cortex become smaller and closer together. Towards the core of the stem the bundles increase in size and are more widely scattered (Killmann and Lim 1985).

The vascular bundle is made up of a fibrous sheath, phloem cells, xylem and parenchyma cells. The frequency of vascular bundles per square unit in oil palm like coconut palm decreases from outside to inside (Table 2) and over the height it shows inconsistent values and increases from the butt end to the top (Table 2) (Lim and Khoo 1986; Sitti et al. 2012). The size of vascular bundles decreases from pith to cortex and with stem height. Lim and Khoo (1987) observed a decrease in width as well as length of vascular bundles over stem height.

Table 2. Distribution of vascular bundles over the stem height of oil palms (Lim and Khoo 1986)

Stem height (m)		1	3	5	7	9	11	Mean	Coefficient of variation
Number of vascular bundles per cm²	P	73	78	87	87	94	105	87	13.1
	C	27	30	37	39	42	46	37	19.4
	I	24	26	30	33	31	32	29	12.3

P= peripheral zone, C= central zone, I= inner zone.

Figure 3 shows the distribution of vascular bundles and their density over cross sections from Thai oil palm wood.

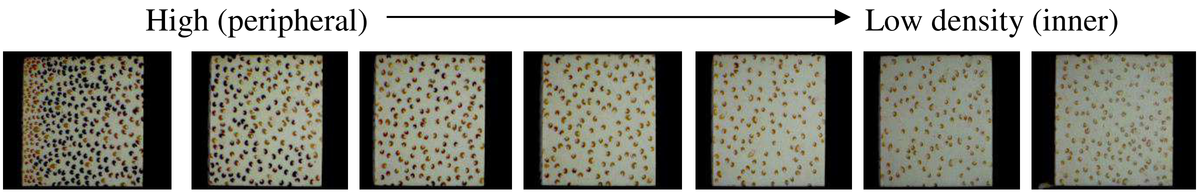


Figure 3. Wood cross sections of an oil palm stem

The parenchymatous cells consist mainly of thin walled spherical cells, except in the area around the vascular bundles. The walls get thicker and darker from the inner to the outer zone (Killmann and Lim 1985).

The most important physical properties are: initial moisture content, density and shrinkage. The initial moisture content increases with increasing amount of parenchymatous tissue from periphery to pith and from bottom to top of stem, where they reach 400% (based on oven dry height). Oil palms show a density decrease from cortex to pith in the lower stem

(Killmann and Lim 1985). Density decrease over stem height has been observed for the outer zone (Killmann and Lim 1985).

Shrinkage values of 8 to 9% were measured (Ho et al. 1985). No anisotropy radial/tangential is reported in literature.

Mechanical properties in oil palms differ up to tenfold across a stem (Killmann and Wong 1988). They are closely related with density and thus with the distribution of vascular bundles. It is that a good understanding of the anatomical, morphological, some basic physical and mechanical properties of the material is essential before it can be put to proper use which shall be done in the present project.

1.3.2 Oil palm distribution

Oil palms are restricted to the tropics and are mainly cultivated in Indonesia, Malaysia and Thailand in Southeast Asia, Nigeria in Africa, Colombia and Ecuador in South America and Papua New Guinea in Oceania (FAO 2009). New plantations continue to be established and existing ones are being expanded (WWF 2011a). Environmental threats due to the effects of oil palm plantations have been broadly studied in Asia, mainly in Indonesia and Malaysia, where 85 per cent of global production of palm oil takes place.

The oil palm is cultivated solely for the oil extracted from the fruits and seeds for various domestic as well as commercial uses. Very little thought has been given to the utilization of other parts of the palms, particularly the trunk. Among the reasons for not doing so is the insufficient information regarding the utilization aspects of the trunk and the ready availability of other alternative material. Thus, felled trunks have had very little economic importance. However, on account of the large quantity available and disposal problems, research work has to be carried out urgently to study the potential uses of this fiber resource.

Generally, the oil palm has an average economic life of 25 years, and during replanting an average of 7.45 tons per hectare of oil palm trunks is generated (Chan et al. 1980). In another study (Table 3), Husin and Hasan (1985) reported that an estimated 260,000 metric tons of oil palm trunk would be available due to replanting in 1985 alone and by the year 2000; the projected availability would be increased to 7 million metric tons per year. The fact is that a solid understanding of the anatomical, morphological and some basic physical properties of the lignocellulosic material is essential before it can be put to proper use.

Table 3. Estimated availability of trunks (10^6 metric tons dry weight) from 1985 to 2000 (Husin and Hasan 1985)

Year	Trunk	Year	Trunk
1985	0.26	1993	4.06
1986	0.37	1994	4.60
1987	0.49	1995	4.37
1988	0.72	1996	4.36
1989	0.97	1997	6.15
1990	1.32	1998	7.48
1991	2.39	1999	7.12
1992	3.29	2000	7.02

1.4 Date palm (Phoenix dactylifera)

The date palm is one of the oldest trees from which man has derived benefit, and it has been cultivated since ancient times. It is the only indigenous wild desert plant definitely domesticated in its native harsh environments (Zohary and Hopf 2000). Date palms are historically very important because they are a source of food that has supplied nutrition to millions of people over thousands of years.

Figure 4. The True date palm Phoenix dactylifera, left: side-view, right: view from below (from Bergman 1977)

Date palms retain their value for cultivators as they give a wide range of products and services, including many necessities of life.

Phoenix dactylifera is a typical tree of the desert oasis and rivers. It likes high temperatures, dry air and sunshine. Rains or high atmospheric humidity late in the development of fruit or during blossoming limit date growth to about the same extent as inadequate heat. The palm is therefore confined to arid or semiarid regions. Therefore, date palms are planted, where they will be able to reach the groundwater level at a maximum depth of 6 m.

In 2006, world production of dates was about 7 million tons and the top 10 producing countries were Egypt, Saudi Arabia, Iran, United Arab Emirates (UAE), Pakistan, Algeria, Sudan, Oman, Libya, and Tunisia (Raj Bhansali 2010).Table 4 shows the number of date palms in millions in the Near East region.

Table 4. Number of date palms in the Near East region (FAO 1995)

Country	**Number (Million)**
Iran	28.81
Iraq	21.5
UAE	20.8
Saudi Arabia	12
Egypt	11
Oman	8.05
Algeria	7.5
Libya	7
Sudan	7
Morocco	4.5
Tunisia	3.4
Mauritania	1.87
Yemen	1.8345
Qatar	0.7687
Kuwait	0.3527
Bahrain	1
Jordan	0.03
Somalia	0.25

The Table shows Iran, Iraq, UAE, Saudi Arabia and Egypt as leading countries in palm plantations.

Of the estimated 120 million date palms in the world, over two-thirds grow in Arabian countries (FAO 1982). Unfortunately, the date palms grown in this region are under threat from diseases, pests, environmental changes and socio-economic factors (El-Juhany 2010).

The wood and paper industries are facing serious challenges in Iran for sufficient wood supply.

This thesis shall contribute to evaluate the anatomical, physical and mechanical properties of date palm wood. It shall also show the potential use of Iranian date palm wood as renewable cellulosic material in the wood and paper industries based on following:

1- Actually there is a wood deficit of about three million cubic meters per year in Iran and about one million cubic meters of wood is imported.

2- Wood harvesting has been decreasing continually due to a severe forest preservation policy and limited timberland area because of agricultural priority.

3- The Iranian population is growing rapidly, so the demand for wood and wood products increases constantly, which intensifies the pressure on the limited wood resources.

4- A similar situation exists in most date palm growing countries (see Table 4).

These circumstances provide no alternative except to face the issue of fiber recourses. There are about 20 million date palm trees in southern regions of Iran, based on the Ministry of Jihad Agriculture estimations. From these plantations a huge pruning waste of about 15 to 20 kg per tree (in total 400,000 t fiber material from leaves) are available. Considering a (theoretical) rotation period of 50 years, some 400,000 palms are felled annually which provides a wood volume of 400,000-500,000 m^3 stem wood per year. 20% of all date palm plantations are located in Iran; the total wood volume available is about 2-2.5 Mio m^3/year that has good potential as renewable cellulosic material. In addition, there are numerous crownless date palm trunks that remained standing after the Iran-Iraq war (Mahdavi et al. 2010).

1.4.1 Properties of date palm wood

Besides fruit, the date palm over the centuries has also provided a large number of other products which have been extensively used by man in all aspects of daily life. Practically all parts of the date palm are used for a purpose best suited to them (Barreveld 1993). A main division of date palm parts is made as follows (Agoudjil et al. 2011): (a) the palm trunk, (b) the mesh, (c) the leaves (frond base [petiole], rachis, leaflets and spines), (d) the reproductive organs (spathes, fruit stalk, spikelets and pollen) and (e) a number of palm extract as the bunches.

Recently, modern technological developments and improved communications have influenced the use of date palm products (excluding dates). Date palm leaves are an important natural source of fiber where the applications have been extended to almost all fields (Barreveld 1993; Al-Sulaiman 2002; Al-Sulaiman 2003; Kahraman et al. 2005; Kaddami et al. 2006; John and Anandjiwala 2008; John and Thomas 2008; Gupta et al. 2009; Janaun and Ellis 2010). On the other hand, also the date palm as a raw material source for industrial purposes must be considered.

The trunks are shorter than those of the Canary palm and typically about 9 to 12 meters. The trunks show a knobby appearance on the trunk surface from tissue from the old, removed leaves bases after pruning (Figure 5).

Figure 5. (a) Multiple date palms in a row, (b) a close-up of the knobby trunk, (c) close-up of the petioles with; yellow color (from Bergman 1977)

Al-Suhaibani et al. (1988) carried out a survey on 19 palm orchards in Saudi Arabia and measured several physical properties such as tree spacing, tree height, trunk circumference, and bunch spacing. Ahmed et al. (1992) obtained physical data to be applicable in palm processing. They measured tree features such as age, height, trunk circumference, spacing and cutting resistance of the leaves. Shamsi et al. (2005) described physical properties like the date palm's visual appearance, yield, fruit quality, tree age and number of bunches to be applicable in precision agriculture.

1.4.2 Distribution of date palm

There are about 13 different species of the genus Phoenix, all are members of the date palm group. Their natural distribution ranges from the Canary Islands across northern and southern Africa into the Middle East, far south Europe, and Asia. The height of the stem can vary. Worldwide, there are approximately 105 million date palm trees covering an area of 800,000 ha (FAO 2006).

Worldwide, an estimated excess of 1,200,000 tons of petioles, 410,000 of leaves and 300,000 of bunches are produced annually. Therefore, from economic and environmental point of view, the utilization of fiber from date palm wood waste is a promising project. It seems that the use of date palm fiber as reinforcement for composites was the subject of many studies (Al-Sulaiman 2002, 2003; Kahraman et al. 2005; Papadopoulos 2005; Sanchez 2005; Kaddami et al. 2006; John and Anandjiwala 2008; John and Thomas 2008; Kriker et al. 2008). However, there is no literature regarding the anatomical, mechanical and chemical properties of date palm wood. Knowledge of these properties is required in order to optimize the industrial process and materials. My study shall be a part of global trend concerning the study of the potential use of date palm wood as building material. To start this task a global characterization of date palm wood is needed. Thus, this thesis aims to investigate the anatomical and mechanical properties of date palm wood.

1.5 Research objectives

Coconut palms and oil palms grow in tropical regions where the availability of tropical timber declines for several reasons. Parallel to this the demand for timber increases because of growing population and standard living. This gap in timber supply/availability cannot be closed or even reduced by imports as worldwide timber supply becomes scare. The establishment of forest plantations is slow and for the next 20-30 years, it is not likely that a huge amount of forest plantation timber appears on the market. The fiber resource from 12 Mio ha coconut palm and some 20 mio ha date palm (in 2030 may be some 30-40 mio ha) could contribute to reduce the gap between demand and supply with wood. The main region of population development and economic development is Asia (Southeast-Asia plus China and India) where 75-80% of all coconut palm and oil palm plantations are located.

A slightly different situation is related to date palm as the third important palm species. Date palm grow in semiarid areas (total about 20 Mio palms which means some 200,000 ha), mainly in Middle East and Northern Africa, where a timber shortages happens even throughout the history and the gap between timber demand and supply is rather big.

Overall it is assumed that palms will play an increasing role in natural fibers supply for the wood sector in total.

But palm fibers are very much different from "normal wood fibers". Tree trunks, leaves and fruit stands are the main fibers sources of which the trunk is closest to "normal wood" in its composition, structure and shape of the trunk. A total availability of 200 mio m^3/year or more of trunk volume (~ 75% oil palm, 20% coconut palm and 5% date palm) challenges research and development for utilizing this material.

Palms are monocotyledons which mean that the structure of the trunk and therefore the "wood" is different to "normal/common timber". This is mainly relevant for the tissue structure and composition, density, water content, ash and silica content and sugar/starch content. These features are much relevant for palm wood processing, product design and product properties/performance.

One basic area of concern for wood utilization are the physical/mechanical properties of the material. Little systematic and comprehensive research exists (see chapters 2.1.2.2 and 2.1.2.3). Quite many publications deal on one side with structure and composition of palm wood or physical/mechanical properties on the other side.

To close the gap between the knowledge of structure and physical/mechanical properties of palm wood this research project was established.

The goal(s)/objectives of this project are:

1. The investigation shall be addressed in order to reduce the negative impacts to enhance the economic development and to open up additional sources of income to small farmers. The aim of these basic studies is to develop a mechanical model in order to explain most mechanical properties from the density of the wood. This will lead to improved grading techniques of processed lumber. The wide variation and moisture content requires fast and good grading in order to improve industrial processing and general use.
2. Another part of the project deals with properties relevant for the use in various applications like the building sector (load bearing and decoration), furniture and handicrafts. Furthermore, the project aims for the introduction of modern adequate utilization of palm wood, and the improvement of timber conversion.
3. The overall aim of this study is to investigate the relation of structure and physical/mechanical properties to enhance better understanding characteristics of coconut, oil and date palm.

The detail objectives expected to be achieved at the end of this research work, are spelt out as follows:

a) Improved knowledge of the structure/anatomy of coconut, oil and date palm stem wood, including macroscopic and microscopic structures,

b) Determination of wood zoning in transverse direction of the trunk in order to improve grading of palm timber,

c) Determination of wood properties, mainly physical and mechanical properties,

d) Improve knowledge of relation of wood structure and properties to develop a basis for improved processing and utilization of palm wood.

2. Overview of current knowledge from research

This chapter contains the review of related literatures which is divided into three subchapters: coconut palm, oil palm and date palm.

2.1 Coconut palm

The research of coconut palm has been done in great amount and depth. Because this palm is widely distributed quite a long time and the stem wood is competitive to commercial timber species in many product areas. Several aspects of these research reviews are described and discussed in the following, particularly coconut palm wood as a raw material source and its anatomical, physical, mechanical and chemical characteristics.

2.1.1 Coconut palm trees as a raw material source

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 of the world as posts for traditional housing and various temporary buildings. The uppermost (immature) portion of the stem has been used as firewood for households in the manufacture of lime and for bricks and tiles (Ohler 1999). In 1997 the total world area planted with coconut palms was about 12 million ha, more than 90% of which was in Asia (APCC 1998). Major coconut producers were Indonesia, Philippines and India. On average, in 1993, about 30% of the plantations in Asia were over-aged while in the Pacific it was over 45%. There is considerable variability between countries (APCC 1998). 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. In the Maldives, coconut wood has been traditionally used for building fishing boats (Mead 2001). With entire plantations becoming over-aged and being felled and processing technologies were partly developed, commercial use of coconut wood started during the 1970s. Depending on its original position in the stem, the main potential end-uses for coconut wood are for wooden construction, paneling, stairs, window and door jambs, flooring and power poles (Mead 2001).

2.1.2 Characterization of coconut palm wood

2.1.2.1 Anatomical features of coconut palm wood

Coconut palms are monocotyledons. Morphologically, the mature coconut stem consists of a wide, unbranched, central cylinder surrounded by a narrow cortex (Cousins and Meylan 1975) shown in transverse section in Figure 6.

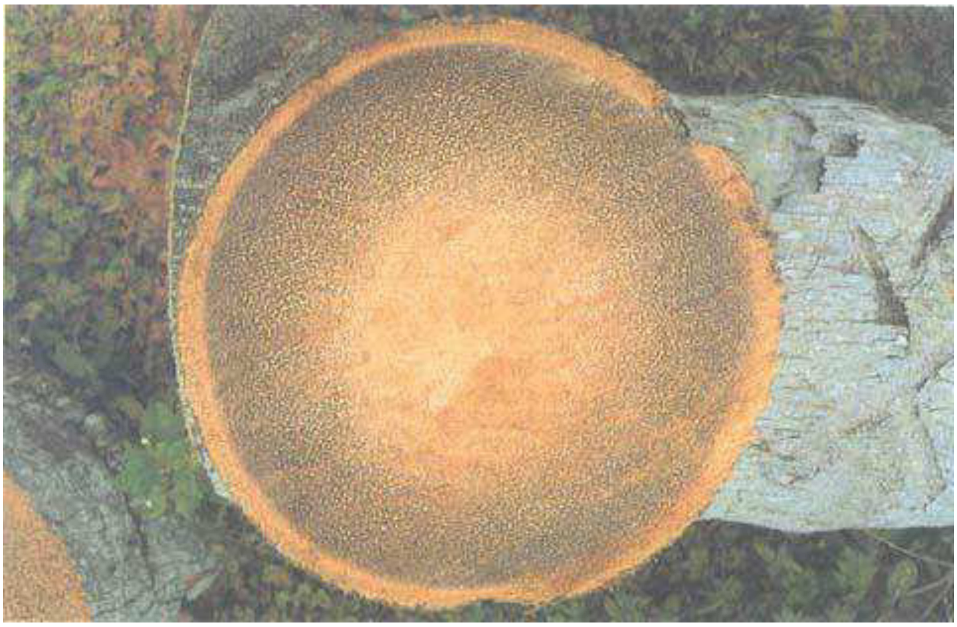


Figure 6. Transverse section of a coconut palm stem (Killmann 1983)

Cousins and Meylan (1975) state: "Apart from the specialized superficial layers, this cortex is largely made up of unspecialized ground parenchyma" containing "numerous small longitudinal fibrous strands. Apart from the large leaf traces, which extend across the cortex from each leaf-based into the central cylinder, cortical vascular bundles are always few and small".

"The central cylinder is abruptly demarcated from the cortex by a wide peripheral sclerotic zone made up of congested vascular bundles separated from each other by narrow layers of parenchyma. Since each vascular bundle has a massive radially-extended fibrous sheath external to the phloem and the ground parenchyma becomes sclerotic, this zone forms the main mechanical support of the palm-stem".

"The inner part of the central cylinder contains widely scattered vascular bundles and there is a gradual transition from the concentration of bundles in the peripheral zone, to this less dense tissue".

They continue: "the structure and distribution of the vascular bundles, as seen in transverse section of the palm-trunk is related to their course in the stem before they exit at the nodes as leaf traces. Since the structure of each bundle varies considerably throughout its length, and since a single section includes parts of different bundles at all possible levels, the structure of the vascular bundles (VBs) seen in transverse and longitudinal section of a single stem appears to vary considerably. External to the phloem, each VB has a fibrous sheath which is always less developed than the peripheral bundles. The xylem is always sheathed by parenchyma. The phloem is in a single strand. The xylem usually contains two wide metaxylem vessels". Figure 7 shows clusters of vessels surrounded by a fiber cap, both forming in VBs.

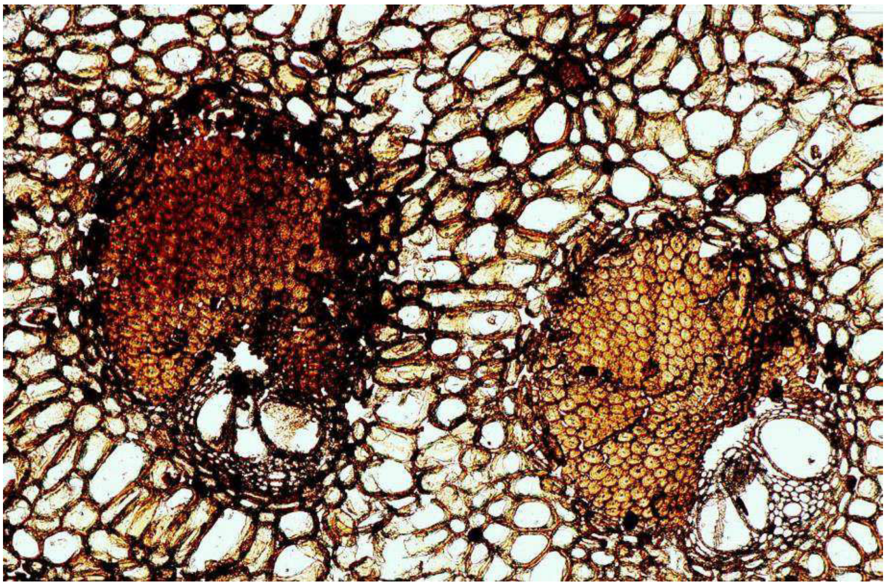


Figure 7. Transverse section from the central zone of stem

The thick-walled fibers, their collenchymas, are seen to have a multilayered structure (Figure 8).

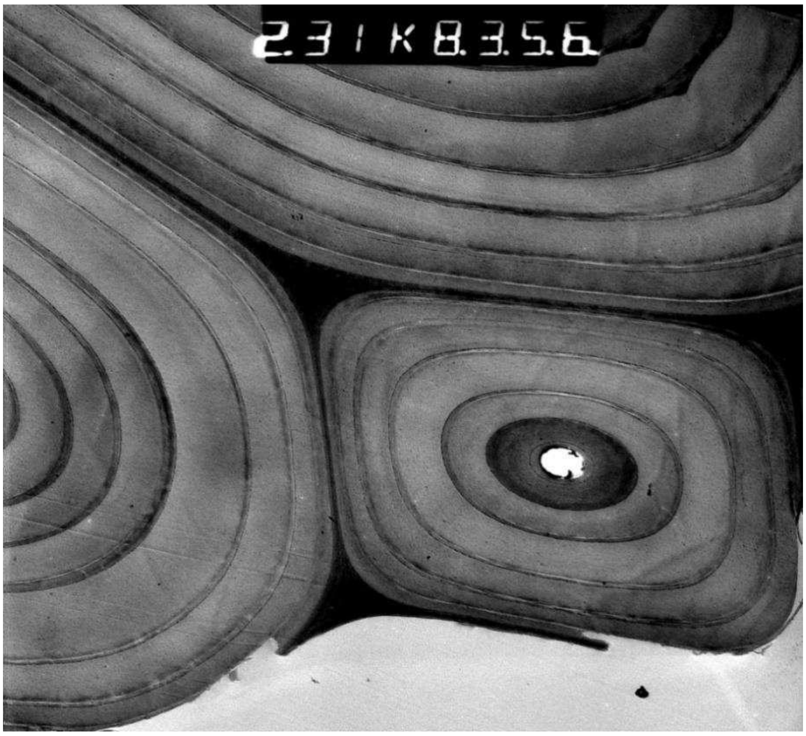


Figure 8. Thick walled fibers from the vascular bundlesshowing layered structure

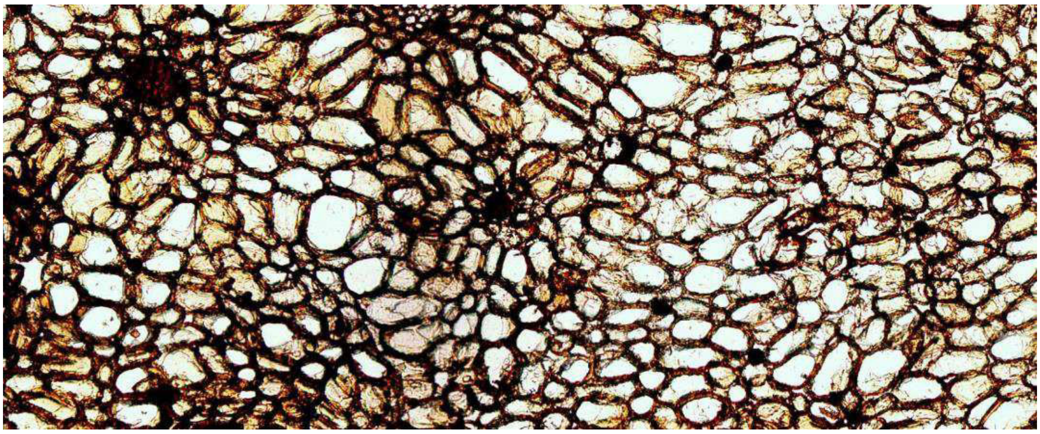


Figure 9. Parenchyma ground tissues

2.1.2.2 Physical properties of coconut palm wood

2.1.2.2.1 Moisture content

Richolson and Swarup (1976) 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 center of the central cylinder. Moisture content showed a high correlation with basic specific gravity (Kloot 1952). Low density means less VB and more parenchyma; this resulted in higher water storage capacity or higher moisture content.

Romulo 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 stems 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. A typical moisture distribution pattern is shown in Figure 10.

Killmann (1983) measured that the moisture content is closely related to the oven-dry density; hard timber, 600 kg/m³ and more, has a low moisture content and soft timber a high one. 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 behavior (equilibrium moisture content, EMC). Frühwald 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 main constitutes, holocelluloses and lignin.

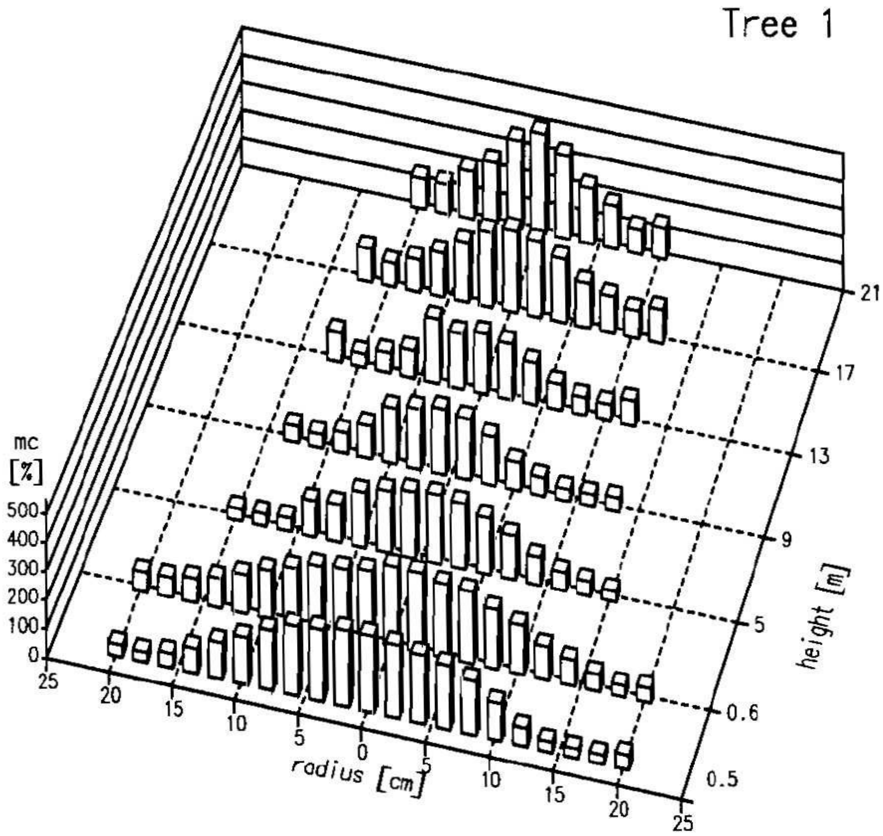


Figure 10. Moisture distribution across and along the stem of tree (Frühwald et al. 1992)

2.1.2.2.2 Shrinkage

The dimensional stability of the wood is determined by the shrinkage/swelling anisotropy and the fiber angel within in the trunk.

Shrinkage and swelling can cause defects such as checks and split. Unlike conventional wood where tangential shrinkage is almost twice the radial shrinkage, the tangential and radial shrinkage of coconut palm wood in these two axes is not significantly different (Romulo and Arancon 1997).

As observed by McConchie (1975) and Richolson and Swarup (1977), there is little difference between tangential and radial shrinkages; on average, tangential shrinkage is slightly higher than radial shrinkage. The data for longitudinal shrinkage are very inconsistent but in any case very low.

Shrinkage/swelling values are generally related to density that means they increase from the center to the bark. They also increase slightly up to about 10 m stem height and then decline. Shrinkage is closely correlated with the amount of VBs per square unit as they also dominate the density.

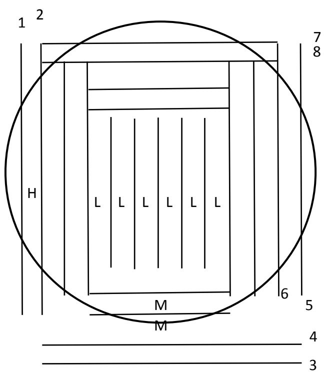
Evidence on shrinkage values of coconut palm wood is somewhat contradictory. Volumetric shrinkage (green to 0% mc) of 10% for wood from the outer portion and from 5% to 7% for intermediate and center portions was reported by Richolson and Swarup (1976) and Killmann (1983) with little height variation. Similarly, McConchie (1975) observed a 10% volumetric shrinkage at the periphery but up to 22% for low density wood from the core. Frühwald 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 wood. Longitudinal shrinkage is very low (under 1%). Low density wood (less than 200 kg/m^3) shows a marked tendency towards cell collapse.

2.1.2.2.3 Density

Coconut wood shows a wide range in density within the trunk both crosswise and lengthwise. Because of its inhomogeneity, Oduor and Githiomi (2009) stated that the wood is classified as ranging between 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 bottom dermal portion of old coconut palms (Romulo and

Arancon 1997). Based on many years of practical experience with coconut wood in constructions, Sulc (1983) suggested the introduction of three density groups: high density (hard, over 600 kg/m^3), medium density (medium, 400-600 kg/m^3) and low density timber (soft, below 400 kg/m^3). Between 15 and 20 m even the outer zone of the stem lies in the medium density range while center and top are already of low density quality (Jensen and Killmann 1981).

The density at any particular height and cross-section increases with the age of the palm tree. There are three density areas as indicated in Figures 1 and 11.



H high density HD
M medium density MD
L low density LD

Figure 11. Typical sawing pattern for palm logs; 1…x sequences of cuts

2.1.2.3 Mechanical properties of coconut palm wood

All mechanical properties which define the use as a timber are closely related to density and thus with the distribution of parenchymatous tissues and VBs. This inhomogeneity influences the methods of processing as well as the uses for the coconut wood. 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). Kloot (1952) compared the average bending strength of full size palm logs with that reported in literature for other commercial timbers such as: Red pine (green) 48 MPa, Lodgepole pine (air-dry) 44.1 MPa and Western red cedar (22% mc) 47.9 MPa. Bending strength of coconut palm wood was determined as 47.4 MPa. Espiloy (1977) investigated coconut trunks for power and telecommunication poles. They 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 MPa and MOE of 6,000 MPa.

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

Guzman (1989) investigated the mechanical properties such as bending strength, compression parallel to grain and shear strength of Mexican coconut wood and compared them to the other 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 center. Density influenced strongly all mechanical properties tested; higher density values were always associated to higher properties values. Coconut wood was highly variable regarding their physical and mechanical properties. He stated that the average MOR values at various positions shown that those values are indicated a gradual decrease in MOR along the trunk depth not understandable English. 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 wood were higher compared to E. cyclocarpum) but lower compared to Q. castanea.

Frühwald et al. (1992) investigated the mechanical properties such as bending strength and MOE, compression strength, shear strength and impact bending of Indonesian coconut wood. They concluded that strength properties of coconut wood are within the range of common traditional timbers, though generally about 20-30% lower when compared on the basis of matching 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.

Frühwald et al. (1992) stated that in addition to the mechanical strength of coconut wood, also nail and screw holding is lower than that of traditional timber species of comparable density. Resistance to splitting might be a problem, therefore adequate measures such as pre-boring for nailing and screwing operations are required.

2.1.2.4 Chemical properties of coconut palm wood

The main wood constituents of coconut wood are similar to common timber species, but it contains 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-value is 6.2 (Gibe 1985; Romulo and Arancon 1997; Poulter and Hopewell 2010). Outer zones of coconut 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 (Li 2004). Cellulose is the main source of the mechanical properties of wood (Janssen 1995). The cellulose content of coconut wood, about 42%, is similar to that of most wood species (Rydholm 1965); comparable to that in softwoods (40-52%) and hardwoods (38-56%). Its content consistently decreased from the outer to the inner zone. The cellulose content is in the range to make coconut suitable for the paper and pulp industry (Li 2004). The outer zone has the highest lignin content. There is no significant difference among middle and inner zone of coconut wood. The higher lignin content contributes greatly to the higher strength properties of the outer zone. The lignin amount of 25.1 % place coconut wood at the end of the normal range of 11-27% reported for non-woody biomass (Bagby 1971) and closely resembles the range reported for softwoods (24-37%) and hardwoods (17-30%) (Fengel and 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, sulfates, carbonates, or metal ions (Rydholm 1965). Coconut wood has significantly higher ash content ($0.25\text{-}0.75_{\text{average}}\text{-}2.4\%$) 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 wood can adversely affect processing (Li 2004). The high silica (hydrated silicon dioxide) content of palm woods is well known to saw-millers and is, for example, a major obstacle to the use of coconut wood (Coconut Stem Utilization Seminar 1977).

2.2 Oil palm

2.2.1 Oil palms as source of a raw material

The oil palm tree is indigenous to the tropical forests in West Africa. It was introduced to the Bogor Botanical Garden of Indonesia in 1848, and first planted in Malaysia as an ornamental plant in 1871 (Basiron et al. 2000). Much later plantations were established in Malaysia to produce palm oil. The plantation area was small for long time but rapidly increased from year to year, especially between 1975 and today, as illustrated in Figure 12. Oil palms have become one of the most valuable cash crops in Malaysia and later in Thailand and Indonesia. Oil palm trunk (OPT) is abundantly available, and it is a less expensive lignocellulosic raw material as compared to commercial timber. Using oil palm biomass as a raw material to produce value-added products will not only reduce the overall costs of production but will also increase economic returns.

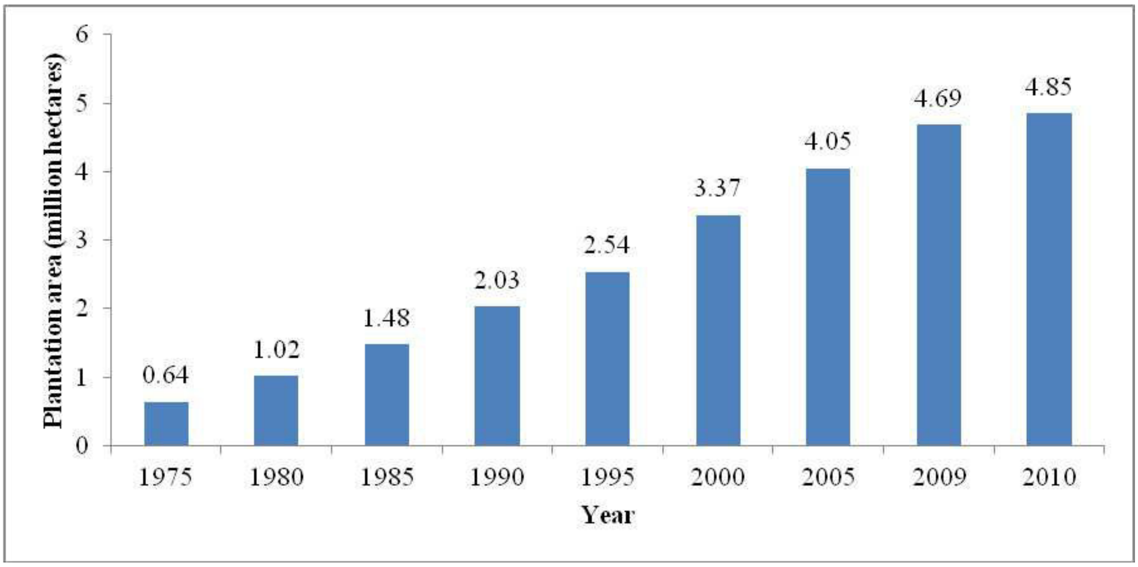


Figure 12. Plantation area of oil palm in Malaysia from 1975 to 2010 (Malaysia oil palm statistic 2010)

Today most applied research towards product manufacture focuses on veneer and plywood manufacturing. Oil palm wood (OWP) can also be used in laminated products such as laminated veneer lumber and both interior and exterior plywood (Nordin et al. 2004; Sulaiman et al. 2008). Another product area of interest is solid wood for interior use. But wood drying is one of the challenges inherent to solid wood products (Kurz 2013). Low density wood is gaining interest for light weight construction as block board with oil palm core for light weight furniture (Bockel 2013).

Several studies exist on the use of oil palm wood for structural purposes. Jumaat et al. (2006) investigated its use as trussed rafters. Results indicated that certain portions of the trunk had good potential for use as structural components. Further, they concluded that oil palm wood has the potential to be used as roof trusses with some technical modifications and proper grading of the trunk and the lumber respectively.

It was reported that some producers in Thailand/Malaysia use oil palm wood for MDF-manufacture but only to a very small percentage (<5%) of the whole material input (Frühwald 2014). Akrami and Frühwald (2014) reported on the manufacture of oriented strand board (OSB) and have found the board properties were almost comparable to common OSB type 2.

Many research projects dealt with the use of oil palm empty fruit bunches (EFB) and oil palm fronds (OPF) for board manufacture and some project also with paper manufacture. Khozirah et al. (1991) described that OPW has also been utilized as a cellulosic raw material in the production of panel products such as particleboard (Teck and Ong 1985), medium density fiberboard, mineral-bonded particleboard, block board (Choon et al. 1991), pulp and paper (Mohd et al. 1984) and cement board (Schwarz 1985; Kochummen et al. 1990). Other fiber resources from oil palms (except the stem wood) are OPF, EFB and oil palm shell (OPS). The availability of this (fibrous) material is even bigger compared to the stem wood (Table 5).

Pruning fronds are constantly generated in the plantations and are mainly used in inter-row mulching (Erwinsyah et al. 1997). But a certain amount is generated at the time of replanting, the EPF and the shells from OPF are available year round at the palm oil mills.

Table 5. Availability of oil palm wastes from 1994 to 1999 in Indonesia (Erwinsyah 2004)

Year	Empty fruit bunches (x 1000 tons)	Fronds from pruning (x 1000 tons)	Fronds from replanting (x 1000 tons)	Oil palmtrunks (x 1000 tons)
1994	4,008	18,041	1,443	6,332
1995	4,631	20,249,860	1,619,988	7,107,700
1996	5,142,685	22,495,140	1,799,611	7,895,794
1997	5,738,847	25,160,790	2,012,863	8,831,437
1998	6,268,426	27,798,820	2,223,905	9,757,385
1999	6,722,069	29,570,790	2,365,663	10,379,347

Similar figures were reported by Husin and Hasan (1985) for Malaysia.

2.2.2 Characterization of oil palm wood

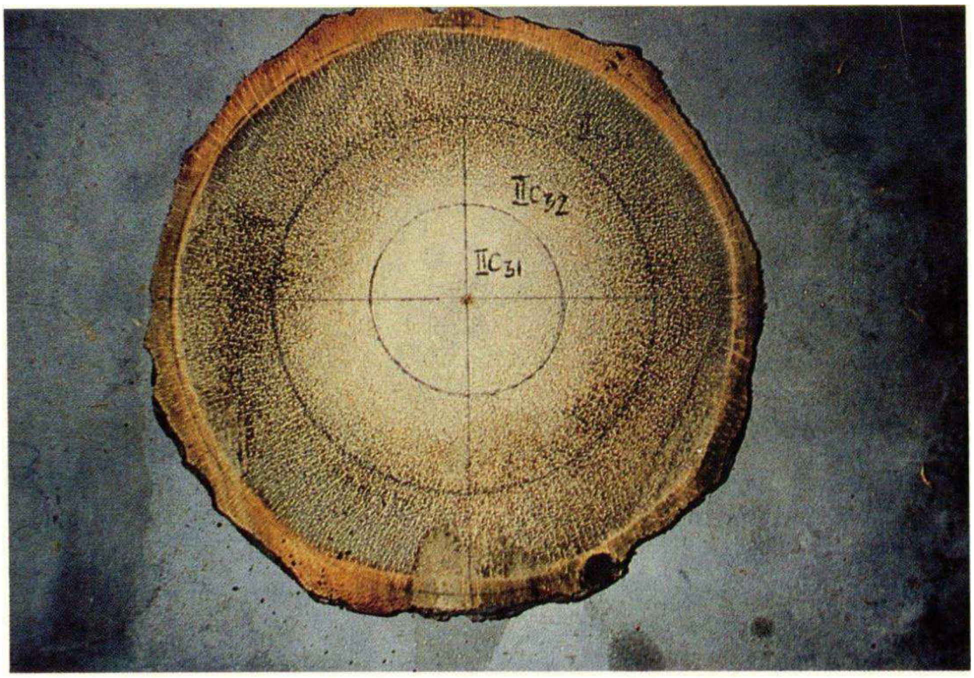


Figure 13. Cross-section of an oil palm stem (Khozirah et al. 1991)

2.2.2.1 Review of anatomical characteristics

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 in not comparable to the wood of angiosperms and gymnosperms (Tomlinson and Zimmermann 1967). Thus, unlike the wood of the latter which is mostly secondary xylem, the wood of palms consists of primary vascular bundles embedded in parenchymatous tissue (Parthasarathy and Klotz 1976). The growth and increase in diameter of the stem result from the overall cell division and cell enlargement in the parenchymatous ground tissue together with the enlargement of the fibers of the vascular bundles. Looking at a cross sectional view of the oil palm trunk, Killmann and Choon (1985) distinguished three main parts, namely cortex, peripheral zone and central zone. Basically, the outer zone of the stem or trunk just beneath the bark is a narrow cortex which is approximately 1.5 to 3.5 cm wide. The cortex is largely made up of ground parenchyma with numerous longitudinal.

The zone immediately after the cortex is the peripheral zone composed of narrow layers of parenchyma and congested vascular bundles giving rise to a sclerotic zone which provides the main mechanical support of the palm stem. In Elaeis guineensis the peripheral zone appears to consist of fusion bundles so that the structure of individual bundles is very irregular. The peripheral zone usually comprises about 20% of the total disc area. The inner zone, which occupies about 40% of the total disc area, on the other hand, consists of larger and widely scattered vascular bundles (Lim and Khoo 1986).

The central zone, however, is considered as the transitional zone between the peripheral zone of concentrated bundles and the inner zone of widely scattered bundles (Lim and Khoo 1986).

The central zone, which makes up about 80% of the total are, is composed of slightly larger and widely scattered vascular bundles embedded in the thin wall parenchymatous ground tissues. Towards the core of the trunk the bundles increase in size and are more widely scattered (Erwinsyah 2008).

Vascular bundles: The structure and distribution of vascular bundles as seen in the transverse section of oil palm vary considerably from one zone to another in terms of size and their orientation. Basically, each vascular bundle is basically consists of a fibrous sheath, phloem cells, xylem and parenchyma cells (Lim and Khoo 1986).

According to Lim and Khoo (1986), in the longitudinal direction, the number of vascular bundles per unit area decreases towards the inner zones and increases from the butt end to the top of the palm. This observation was contrary to the findings of Tomlinson (1961) who stated that the number of vascular bundles per unit area of the stem was approximately the same throughout the height. Killmann (1983) in his study of the coconut palm stem (Cocos nucifera) reported that the number of vascular bundles per cm^2 had a high linear correlation to stem height with the amount of vascular bundles per unit area increasing with stem height on all three axes and decreasing radially from the outer to the inner zones.

The xylem of the vascular bundles is always sheathed by parenchyma cells and contains mainly one or two wide vessels in the peripheral zone and two or three vessels of similar width in the central and core zone (Lim and Khoo 1986). This finding is contrary to that made by Tomlinson (1961) who postulated that only 1-2 wide vessels are present in a vascular bundle of the Elaeis palm.

Extended protoxylem, reduced vascular tissue and small bundles with little fibrous tissue are also commonly found scattered among the wider bundles in the core zone. Lim and Khoo (1986) further stated that the distribution of fibrous strands depends largely on the number of bundles present.

The peripheral zone normally contains a large number of radially extended fibrous caps and therefore, provides the mechanical strength to the palm. Apparently, a fiber keeps developing its secondary wall during its life time. Thus, the basal parts of palm stems, being older, normally have fibers with better developed secondary walls than do the top parts. The secondary walls in old fibers usually display a characteristic multilayered structure (Parthasarathy and Klotz 1976).

The phloem cells, in single strand, are present between the xylem and fiber strands. In the peripheral sclerotic zone where the bundles are generally smaller and in irregular shape, the phloem tends to be reduced in size and in some cases almost disappears. The area occupied by the phloem, which is in the form of an inverted triangle, increases in size as the bundles become larger in the central zone.

Parenchymatous tissue: The ground parenchymatous cells consist of mainly of thin-walled spherical cells except in the area around the vascular bundles. The walls of these parenchyma cells are progressively thicker and darker from the inner to the outer zone. Similar observations were made by Kloot (1952) in his study of the coconut palm.

2.2.2.2 Physical properties of oil palm wood

2.2.2.2.1 Moisture content

Killmann and Choon (1985) stated that initial moisture content of the oil palm wood varies between 100 and 500%. A high correlation was found between the moisture content and stem height for all the three zones of the oil palm (Lim and Khoo 1986). Although the data in Table 6 describe a quite large variation in moisture content across the stem. This radial variation in moisture content is in contrast to that of the coconut palm in which the moisture content shows a smaller difference (Killmann 1983) which is caused by generally higher density of the wood compared to oil palm.

Table 6. Distribution of moisture content over the stem height and across stem diameter of the oil palm (Lim and Khoo 1986)

Stem height (m)	**Moisture content (%)**		
	Peripheral zone	Central zone	Inner zone
1	120	303	332
3	123	303	335
5	148	369	413
7	159	442	488
9	160	422	505
11	194	435	532
Mean	151	379	434
Standard deviation	27.4	64.2	87.4
Coefficient of variation	18.1	16.9	20.1

Lim and Khoo (1986) stated as well that the MC variation can possibly be explained by the relative amounts of VBs and parenchymatous tissue within the oil palm. The parenchyma contains more water than VBs. With the increase in abundance of parenchymatous tissue towards the apex of the stem where the younger growing regions of the plant lie, and radially from the periphery towards the center "pithy" zone, the increase in moisture content in these directions is thus accounted for (Lim and Khoo 1986).

Bakar et al. (1998) found that based on the depth of the trunk, the highest moisture content was reached at the center of trunk and decrease gradually to the outer zone of trunk. The values were between 258% and 575%.

An increasing number of VBs causes a decrease of parenchyma volume fraction having high capacity in water absorption (Prayitno 1995). Bakar et al. (1998) further observed that, based on the trunk height factor, there was a tendency for the moisture content to decrease from the bottom to the top of the oil palm tree. They predicted that it was influenced by the Earth's gravity where the water distribution to the higher part of the trunk requires higher caviler pressure. Bakar et al. (1998) found that the variant analysis showed that both the trunk height and depth were significant at the level of 0.01 to the value of moisture content.

2.2.2.2.2 Shrinkage

Moisture content and shrinkage are inversely proportional to density. It was reported by Bakar et al. (1998, 1999a, b) that the dimensional stability of the oil palm trunk (OPT) has very low values with variations of shrinkage in the range of 9.2 to 74%. The value of 74% shrinkage is certainly influenced by cell collapse during kiln drying. No wood species is known to have such high shrinkage values (Kollmann 1951).

The volume shrinkage of OPT ranged from 25 to 74% (Bakar et al. 1998). For the trunk cross cut zones the highest shrinkage happens at the central zone and a gradually decreases to the outer zone which is not to explain by density. At a height of 2.75 m, the shrinkage was found to be lower compared to the base of trunk. According to their findings, there was a tendency that a gradual increase in shrinkage value is indicated along the trunk height, except at the height of 2.75 m.

With regard to this phenomenon, Prayitno (1995) further mentioned that it was an anomaly for the oil palm trunk at 2.75 m height. A study by Erwinsyah (2008) showed that the shrinkage in the central zone was about 19.6% ranging from 13 to 23%, while the shrinkage value in inner and peripheral zones were about 16.7% (range 11 to 20%) and 16.8% (range 10 to 23%), respectively.

2.2.2.2.3 Density

As with other monocotyledons the physical and mechanical properties of the oil palm trunk show considerable variability over the trunk, both radially and vertically. The density distribution over the stem is illustrated in Figure 14.

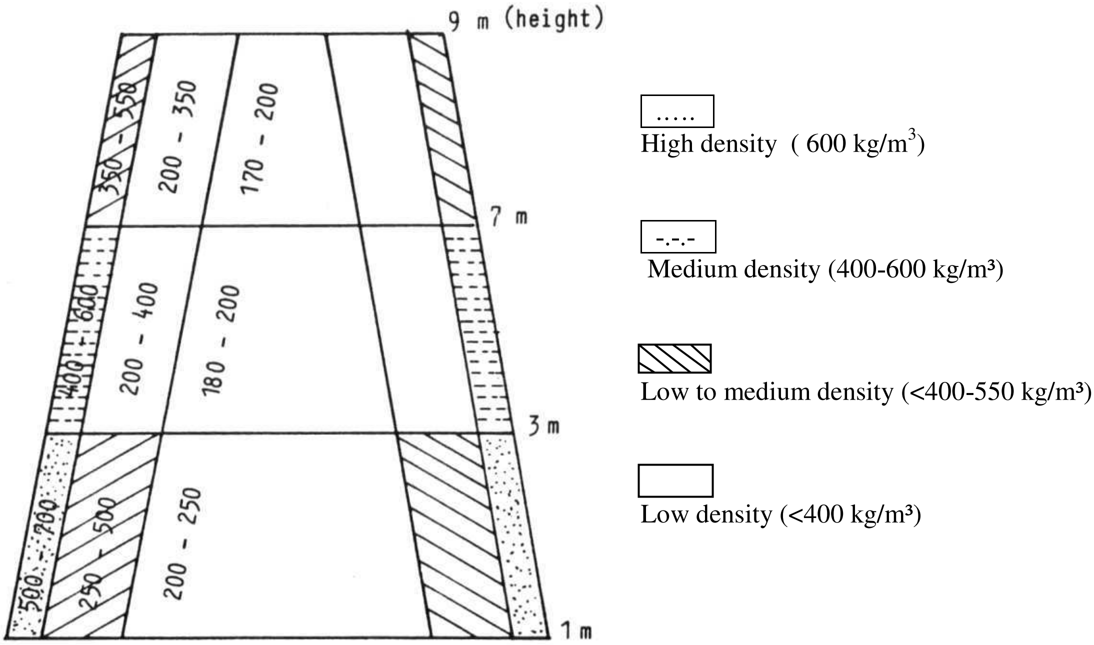


Figure 14. Density variation within an oil palm stem (Lim and Khoo 1986)

The density of oil palms is generally lower than for coconut palms. The reason might be that coconut trees are normally felled at 60 years of age. The lower felling age for oil palms means that there is less lignification and fewer secondary layers in fibers. Therefore oil palms shows a relatively narrow band of high density material (<50 mm wide) near the cortex. Coconut at 60 years of age often has a high density band of 100 mm and wider (Haslett 1990). The density of OPT values range from 200 to 600 kg/m³ (average for the three zones), with an overall average density of 370 kg/m³ (Lim and Khoo 1986). According to the experiment results from Bakar et al. (1998), who conducted an investigation based on the Tenera variety of oil palm, the density was varies between 110 and 400 kg/m^3. Erwinsyah (2008) found the density of OPT ranged from 140 to 600 kg/m³. Prayitno (1995) found a wide variation between 280 and 750 kg/m³ and the highest density value also is on the outer zone, and its value decreases towards the pith. But the density could even be higher in single trees; boards were collected in a saw mill in Malaysia having a density of ~900 kg/m³ (Frühwald 2014). Killmann and Lim (1985) and Killmann and Wong (1988) reported that wood density is directly related to the number and thickening of the vascular bundles and that these increase radially from the core to the trunk periphery and generally with decreasing height in the trunk. Lim and Khoo (1986) stated that the density of oil palm trunk decreases linearly with the trunk height and towards the center of the trunk. These variations are due to several factors: Across the trunk the density is influenced largely by the number of vascular bundles per square unit which decreases towards the center. However, variations in density along trunk height are not so much influenced by the number of VBs but due to their younger age at the top and of the palm. Although higher in number per cm^2 the bundles are smaller in size and the cell walls are thinner (Erwinsyah 2008).

Higher density values in the peripheral zone of the trunk are due to the following reasons (Lim and Khoo 1986):

a) presence of radially extended fibrous sheaths,

b) vessels are less in number,

(c) general absence of extended protoxylem in the outer vascular bundles,

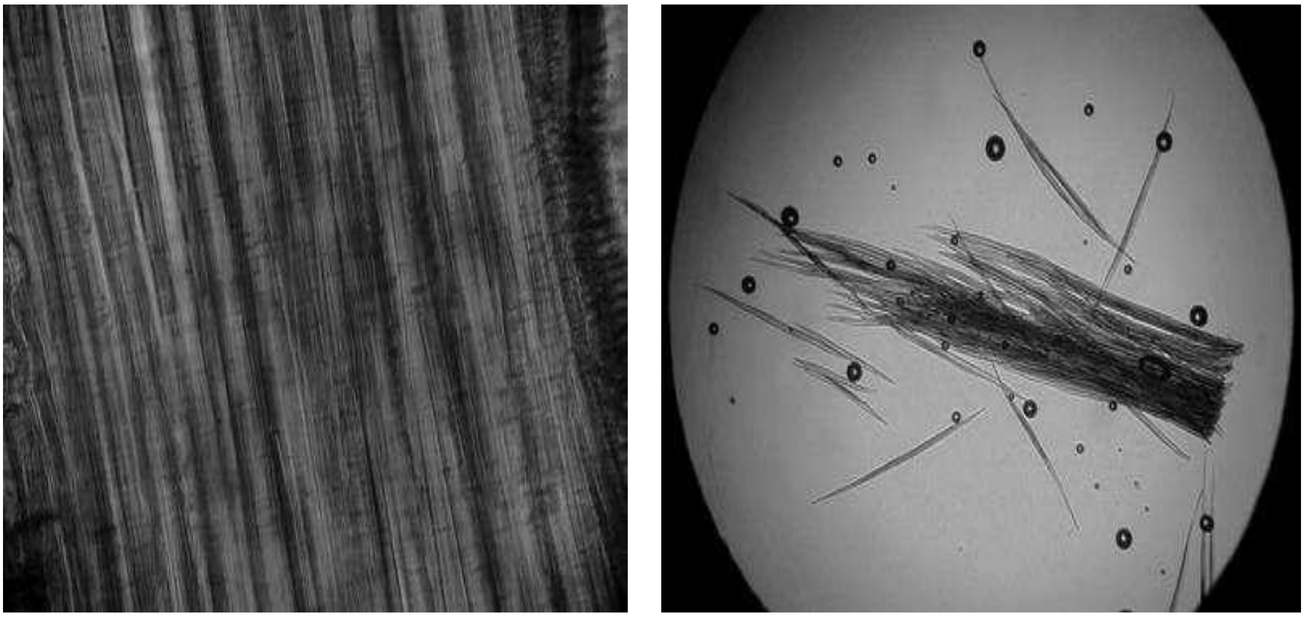
d) progressively thicker walls of the tissue parenchyma cells from the inner to the outer zones,

e) the presence of better developed secondary walls in the fibers.

In another work, Bakar et al. (2005) stated that the outer zone of the trunk is dominated by the vascular bundles (51%) that have a high density, while the inner zone is dominated by parenchyma tissue (70%) that has a low density.

2.2.2.2.4 Fiber dimensions

The fibers of oil palm wood are arranged parallel to the length of the trunk as shown in Figure 15a. Figure 15b shows fibers after maceration of a vascular bundle.



(a) Fibers structure at longitudinal view (b) Fibers from macerated VB

Figure 15. Fiber structure and arrangement at transverse section under light microscopy views (Erwinsyah 2008)

Erwinsyah (2008) found the fiber dimensions of oil palm at various trunk heights to be similar to those of angiosperms, represented by rubber wood (Hevea brasiliensis), and gymnosperms, represented by Douglas fir (Pseudotsuga menziesii) (Table 7). The length of oil palm wood fiber was about 2.04 mm, ranging from 1.9 to 2.1 with average diameter of approx. 26.1 µm, ranging from 22 to 30. It was found that the fiber diameter gradually decreased from the butt end to the top of the trunk. The average values of lumen diameter and wall thickness were about 12.5 µm and 6.8 µm, respectively.

Oil palm stem fibers are comparable in length to fibers from rubber wood, but are much shorter than those of Douglas fir (Choon et al. 1991).

Table 7. Fiber dimensions of oil palm wood in comparison to rubber wood and Douglas fir wood

Fiber dimension	**[1]Oil palm wood**			**[2]Rubber wood**	**[3]Douglas fir**
	2 m	6 m	10 m		
Length (mm)	2.08	2.09	2.00	1.4	3.4
Diameter (µm)	29.2	26.6	22.5	31.3	40
Cell wall thickness	8.08	6.05	6.3	5.0	n.a

1 - Erwinsyah (2008), 2 - Khoo Kean Choon (per. comm. 1990), 3 - Mohamad et al. (1985)

Oil palm wood fibers show a slight increase in length from the butt end to a height of 3 to 5 meters before decreasing continuously towards the top. Longer fibers at the butt end are probably due to more matured fibrous tissue in this region (Killmann and Lim 1985). Lim and Khoo (1986) stated that the fiber length does not show a good correlation with stem height or density. The fiber length distribution of the oil palm stem is quite different from that in the ordinary woody angiosperms and gymnosperms in which the fiber length generally increases from the pith outwards until reaching a constant length. Oil palm fiber length increased from periphery to the inner zone (Erwinsyah 2008). Mean fiber length ranges from 1.76 mm at periphery to 2.37 mm at the inner zone. This might be related to the nature of the palm growth where the overall increase in trunk diameter is due to enlargement of the fibrous bundle sheath, particularly those accompanying the VBs in the central zone (Killmann and Choon 1985). Lim and Khoo (1986) stated that fiber diameter decreases along trunk height because the broader fibers are to be found in the larger VBs (nearer the base of the palm trunk) and vice versa. Similarly, the width decreases from the outer zone to the pith. Little change in cell wall thickness is observed with stem height (Khozirah et al. 1991).

In the conversion of the oil palm stem into pulp, an important relationship to consider is the ratio of the fiber length to the fiber diameter (L/D) or flexibility coefficient. Although the correlation between this factor and stem height is poor, a significant increase is indicated from the outer zone to the inner zones. The higher flexibility values in the central zones of the stem demonstrate the beneficial effects these fibers have on pulp properties, especially the tearing strength (Lim and Khoo 1986). Based on the measurements of Mohd-Nor et al. (1984), the oil palm fibers in the inner zones of the stem have also lower rankle ratios, indicative of thinner cell walls relative to the lumen width, which are favorable for good bonding properties of the pulp.

2.2.2.3 Mechanical properties of oil palm wood

The mechanical properties of wood determine the resistance to exterior forces. Strength is one of the primary criteria for selection of the material for most applications. Mechanical properties follow the density variation observed in the stem both in radial as well as in the vertical direction, as mechanical properties are generally closely related to density. The small ring of the high density wood near the cortex restricts the potential of oil palm wood for sawn timber use for load bearing proposes. The low density wood in the inner zones has low density and mechanical properties and is extremely prone to drying defects. The low strength properties of the wood from inner zones limit the use for various uses (Haslett 1990). Killmann and Lim (1985) investigated the mechanical properties of oil palm trunk (30 years old) and compared it to the other species such as coconut wood and rubber wood. Their findings are shown in Table 8.

Bending strength values are the highest at peripheral lower zone of the trunk and the lowest at the central core of the top zone of the trunk. The development is similar (but not the level) (Killmann and Lim 1985). Variation of the compression strength parallel to grain also follows the same trend as bending strength. Although oil palm wood of lower mechanical properties than other timber species, the compression strength value is comparable to rubber wood at similar density values (Killmann and Lim 1985).

The hardness value of oil palm wood is generally lower than most timber species including rubber wood as well as coconut wood. The hardness of wood from the peripheral lower zone of the oil palm is, however, comparable to those of Norway spruce and poplar wood (Killmann and Lim 1985).

Table 8. Comparison of properties of oil pal wood with those of other species (Killmann and Lim 1985)

Species	Density (oven-dry) (kg/m³)	MOE (GPa)	MOR (MPa)	Compression parallel (MPa)	Hardness (N)
Oil palm wood (30 yrs. old)	220-550	0.8-80	8-45	5-25	350-2,450
Coconut (60 yrs. old)	250-850	31-114	26-105	19-49	520-4,400
Date palm	410	17-27	11-23	6-10	2,000
Norway spruce	300-640	110	66	43	2,140
Beech	490-880	160	105	53	5,650
Poplar	360-560	83	76	36	2,500
Cengal	820	196	149	75	9,480
Kapur	690	132	73	39	5,560
Dark red Meranti	540	127	71	38	3,960
Rubber wood	530	88	58	26	4,320

Understanding of the mechanical properties of oil palm wood from the Tenera variety meanwhile was greatly advanced by Bakar et al. (1999). They reported that mechanical properties of oil palm trunk including MOE, MOR, compressive strength, cleavage strength, shear strength, hardness and toughness decrease close to the center of the base and top of the trunk because the influence of trunk depth factor (diameter) is greater than the effect of trunk length. In the horizontal section, all the mechanical properties decreased sharply from the periphery to the center due to differences in specific gravity and density of vascular bundles in each section.

Bakar et al. (1999) measured that the average MOE values at various positions show a gradual decrease along the trunk height and depth. The MOE value range varied between 2908 kg/cm^2 and 36289 kg/cm^2. For single samples, variation of the MOR also follows the same trend as the MOE. The mean values of MOR for the peripheral, central and inner zones were about 295 kg/cm^2, 129 kg/cm^2 and 67 kg/cm^2, respectively. Statistical analysis of MOE value showed that the differences in trunk depth were significant at the level of 0.01, but for the trunk height the level was only 0.05. This means that in order to produce the homogenous lumber, the trunk depth position should be taken into account, especially in determining the sawing pattern before log processing.

2.2.2.4 Chemical properties of oil palm wood

In order to investigate the chemical properties of oil palm wood, Yusoff et al. (1984) stated that the variation in chemical composition across the trunk at the 1.8 m height level in one tree was difficult to generalize. However, Husin et al. (1985) found that the oil palm trunk has markedly lower lignin and lignocelluloses contents, but shows higher content of extractives as well as water and alkali soluble than coconut and rubber wood. Sulaiman et al. (2009) observed that the chemical composition of oil palm biomass aids in the production of binderless panels. Studies by Hashim et al. (2011) found that of all parts of the oil palm, the trunk contains the highest amount of starch and total sugar. Hemicelluloses and cellulose are desirable in the production of binderless panels. Halimahton and Ahmad (1990) observed that the lignin content was fairly evenly distributed throughout the tree except that the core in the upper zone was slightly deficient in the component while the bottom contained an excessive amount. The lignin content varied between 15% and 21.7%. The results are consistent with the fact that the number of fibrous vascular bundles increases towards the peripheral zone and thickening of the older VBs gives rise to the higher lignin content of the lower trunk. The ash content was also throughout the trunk with the range varying between 3.0% and 3.3%.

Tufashi (2013) studied the chemical properties of oil palm trunks and specifically focused on pH-value, buffer capacity as well as ash and silica content of the oil palm stems. The results of testing along the stem height and stem diameter of oil palm were compared to some other wood species such as larch, pine, beech and oak. He concluded that oil palm wood has a higher pH-value than common timbers. The ash content from oil palm wood has higher as well as the silica content. He concluded that the strong wear and tear of the tools in the processing is strongly related to silica storages.

Table 9 compares the chemical composition of the oil palm stem wood with those of coconut, banana stem, softwood and hardwood species.

Table 9. Chemical composition of oil palm stem, coconut stem, banana stem, softwood and hardwood

Chemical composition	Oil palm[1] stem	Coconut palm[2] stem	Banana[3] stem	Softwood[4]	Hardwood[4]
Holocellulose (%)	45.7	66.7	65.2	60-80	71-89
Alpha-cellulose (%)	29.2	42	63.9	30-60	31-64
Lignin (%)	18.8	25.1	18.6	21-37	14-34
Ash (%)	2.3	2.8	1.5	< 1	< 1

1 - Mohamad et al. (1985), 2 - Escolano and Bawagan (1988), 3 - Abdul Khalil et al. (2006), 4 - Tsoumis (1991)

Generally, coconut wood contains a high percentage of lignin (25.1) but it is still lower than that of soft-and hard wood fibers (14-37%) (Tsoumis 1991). Oil palm stems have lower lignin and holocellulose contents but show higher contents of ash than that of banana stem or wood fibers.

An important contribution for the evaluation of chemical properties of oil palm wood is the research on free sugars and starch carried out by Sudin et al. (1987). Freshly felled oil palm stems may yield up to 10% free sugars and 25% starch (Erwinsyah 2008). Halimahton and Ahmad (1990) reported a total content of free sugars of 2-10% throughout the stem height. For the core zones, higher proportions of free sugars were found as shown by the methanol-water extracts while the peripheral zones had lower proportions. High performance liquid chromatography (HPLC) found sucrose, glucose and fructose as the three main free sugars of the oil palm stem. The level of sucrose remained fairly constant throughout the stem height. On the other hand, the glucose level decreased with increasing stem height whilst that of fructose increased such that in the upper zones these two sugars were present in comparable amounts (Khozirah et al. 1991).

Halimahton and Ahmad (1990) used acid hydrolysis of oil palm wood and found high amounts of sugars ranging between 48%-70%. Their examination of the HPLC trace of the acid hydrolyzate showed the presence of six sugar components namely glucose, xylose, galactose, arabinose, mannose and rhamnose with glucose being the major component (35-48%) followed by xylose (11-16%).

On the basis of standard TAPPI chemical analysis, Bakar et al. (1998), using oil palm trunks of the Tenera variety observed a gradual decrease in lignin content and cellulose from the peripheral to the inner zone, while the starch content increased. Ash and silica contents were found high at the inner zone. The soluble analyses using hot water, cold water, alcohol benzene and NaOH 1% also found high amounts in the inner zone.

2.3 Date palm

2.3.1 Date palm trees as a raw material source

The number of date palm (Phoenix dactylifera L.) planted in Near East region is 140 Million (FAO 1995) with about 50% of the harvest area in Iran, Saudi Arabia and Iraq. New plantations have recently been established in the USA and the southern Hemisphere (Zaid and Arias-Jiménez 2002).

The world date palm cultivation is concentrated mostly in the Near East and North Africa favored by the suitable dry sub-tropical and high temperature climate prevailing in these regions (Sawaya 2000). The major producers of dates in the world are situated in the Persian Gulf and North Africa. Kader and Hussein (2009) reported that in 2006, world production of dates was about 7 million tones and the top 10 producing countries were Egypt, Saudi Arabia, Iran, United Arab Emirates, Pakistan, Algeria, Sudan, Oman, Libya, and Tunisia. This is true as the Arab countries possess the majority of world's date palms and produce the majority of the world's total date crop. The productive economic life of a date palm is not known with precision. A rough estimate is about 75 years; however trees may be replaced when they reach excessive heights because of the difficulty of pollination, pruning and harvesting. For calculation of timber supply a potential life time of 50 years could be used. Taking 140 Million date palm trees with 1 m^3 logs per tree and a life time of 50 years, then about 2.8 million m^3 of date palm wood is available.

When the palms are cleared for replanting, abundant quantities of leaves and stem wood create a disposal problem. Currently, these materials are almost not utilized. Comprehensive information on date palm growing and its numerous products can be found in Barneveld (1993) which updates earlier studies by Dowson (1962, 1982) and Zaid (2002).

Modern technological developments have made it possible to look at the palm as a raw material source for industrial purposes. Stem wood can be split or sawed into construction material. Posts and rafters for huts are fashioned of the wood from the trunk of the date palm, though this wood is lighter than that of the coconut. It is soft in the center and not very durable. That of male trees and old, unproductive females is readily available and used for aqueducts, bridges and various kinds of construction, also parts of dhows. All left over parts of the trunk are burned for fuel.

2.3.2 Characterization of date palm wood

2.3.2.1 Review of anatomical characteristics

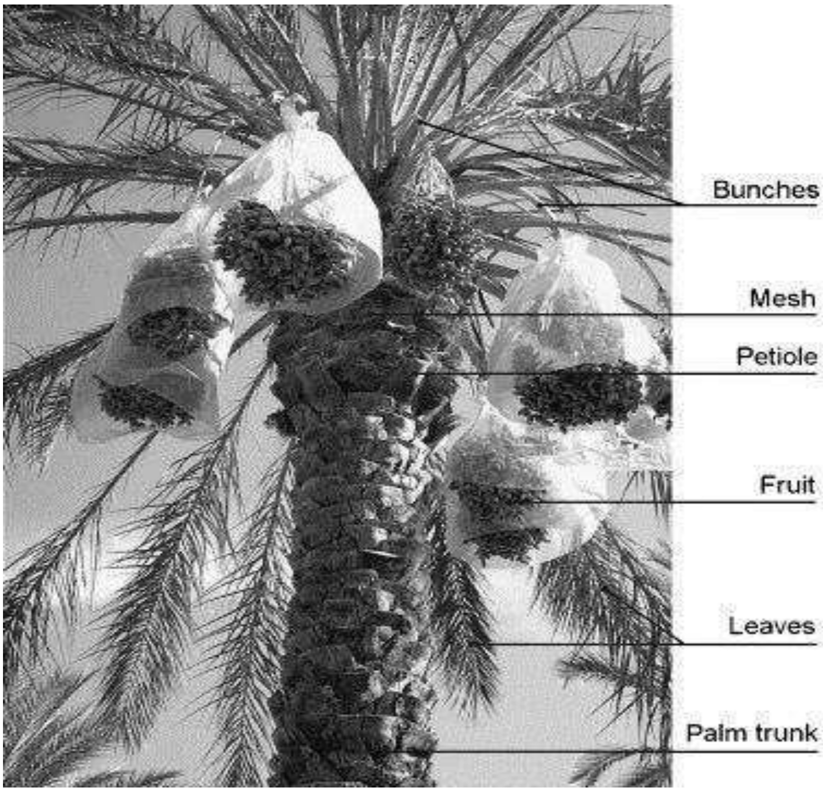


Figure 16. Date palm plant (Agoudjil et al. 2010)

The date palm trunk is cylindrical, straight and has low taper. It is brown in color, lignified and made up of VBs (Arrigoni 1973) inserted in a parenchymatous matrix (Figure 17) which is highly lignified near the outer part of the trunk.

The date palm stem is composed of a narrow cortex and wide central cylinder. The cortex contains numerous fiber bundles independent of the cylinder (Tomlison 1961). In the central cylinder the peripheral area is through the closely spaced vascular bundles clearly separated from central zone with more parenchymatic tissue.

The vascular bundles are generally composed of 2 or 3 metaxylematic vessels; the relative phloematic portion develops in proximity to the point of contact between the two vessels, on both sides. The phloem-xylem system occupies only a marginal portion of the bundle, a considerable part of which is made up of fibers that wrap the conducting elements. The consequence of this cellular arrangement is the lack of any three-dimensional cellular structure, which is found dicotyledons, with its transverse, radial longitudinal and tangential longitudinal sections (Mauro et al. 2009).

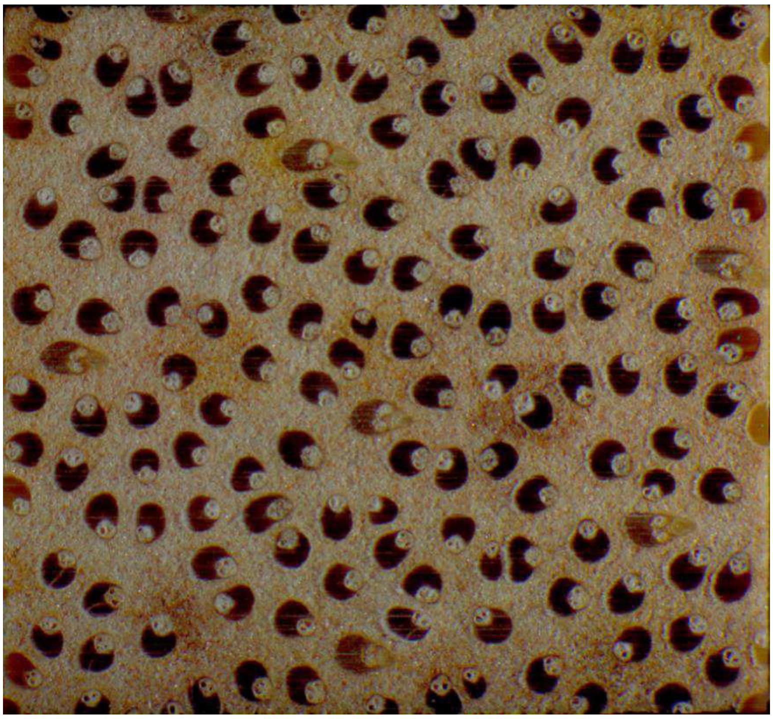


Figure 17. Transverse section of date palm wood under a light microscope

The diameter growth of date palm trunks is not due to cambial activity and it is not connected to the tree's age (Murai et al. 2009). Date palm trunks grow as a consequence of the division and increase of parenchymatous cells. This kind of growth is called "diffuse secondary growth" (Esau 1977) because of VB growth thickening.

2.3.2.2 Physical properties of date palm wood

2.3.2.2.1 Moisture content

No studies were found describing the date palm wood moisture content and distribution. However, as the moisture content variation can possibly be explained by the relative amounts of VBs and parenchymatous tissue within the oil palm (Killmann and Wong 1988) and also the results have obtained in this study, showing the same trend for the amount of vascular bundle from periphery to pith and from base to top of stem in both palms (oil and date) considering the results of oil palm wood moisture content can be expected also for the date palm.

The initial moisture content increases in oil palm with the increase in abundance of parenchymatous tissue towards the apex of the stem where the younger growing regions of the plant life and radially from the periphery towards the center pith region where they reach 400% (based on oven dry height) in oil palm wood (Killmann and Wong 1988) the increase in moisture content in these directions is thus accounted for.

2.3.2.2.2 Shrinkage

Vertical growth of date palm is ensured by its terminal bud and its height could reach 20 meters. Horizontal or lateral growth is ensured by an extra fascicular cambium which soon disappears and which results in a constant and uniform trunk width during the palm's entire life. However, the terminal bud could experience an abnormal growth caused by a nutritional deficiency which leads to shrinkage of the trunk. This stage is mainly caused by drought conditions (Zaid and de Wet 1982).

As for moisture content, no studies were found on date palm wood shrinkage values. However, as the shrinkage is inversely proportional to density with mechanical properties directly proportional to density (Haslett 1990). Results of this study also show that the date palm wood has not significant density variation especially between the inner and outer part of the trunk and from base to top of stem. It can be concluded that only little shrinkage variation and anisotropy radial/tangential occurs. But absolute figures for shrinkage/swelling have to be tested.

2.3.2.2.3 Density

The density the date palm trunk show no significant difference within the trunk, both radially and vertically. Tufashi (2013) studied the physical properties of date palm trunk and specifically focused on the density of date palm stem. The results of testing along the stem height of date palm were compared to oil palm and some other native wood species such as larch, pine, beech, and oak. He concluded that the date palm stem shows only small variation regarding to the density and that density of date palm wood is higher than that of oil palm, larch and pine, butslightly lower than beech and oak.

Table 10 compares the average density of date palm stems with those of oil, larch, pine, beech and oak stems.

Table 10. Average density within the stem (air dry) of date palm, oil palm, larch, pine, beech and oak (Tufashi 2013)

	Date palm stem			**Oil palm stem**			**Larch**	**Pine**	**Beech**	**Oak**
	Base	Middle	Top	Base	Middle	Top				
Density (g/cm³)	0.66	0.64	0.64	0.42	0.41	0.45	0.60	0.52	0.71	0.70

Based on the average density values of the date palm stem (ranges between 610 kg/m³ and 675 kg/m³), Tufashi (2013) stated that grading the stem into three zones periphery, center and inner zopne, is not necessary before processing because the density variations over the cross section are marginal. Also, along the stem height a sorting into three stem height - bottom, middle height and top is not required due to the similarity in the densities in all stem heights.

No more referenceswere found regarding to the date palm stem density. Killmann (1993) evaluated physical properties measured by another source (Rogers et al. 1982) who worked on the canarian date palm (Phoenix canariensis) Five palms were evaluated but age and height were unknown (Killmann 1993). The known values in the literature for stem density of date palm (Phoenix canariensis) vary between 300-540 kg/m³ (Killmann 1993).

2.3.2.2.4 Fiber dimensions

Date palm wood fiber (DPWF) is one of the most available natural fibers in the Middle East, especially in Iran and the Persian Gulf region. Generally, organic fiber has a good market possibility in many sectors.

The primary function of fibers is to provide mechanical support to the date palm tree, particularly in the peripheral zone of the trunk. Mechanical performances of natural fibers are influenced by complex interactions between numerous external variables and inherent structural characteristics at molecular, macromolecular and microscopic levels. Similar effects result from other factors such as cellulose, lignin and hemicelluloses content, degree of polymerization or crystallinity, microscopic and molecular defects of fibers' wall and the presence of moisture or other introduced chemicals (Rowell et al. 1997).

The fibers of date palm wood are arranged parallel to the length of the trunk. The dimension of date palm wood fibers compared to those of angiosperms, represented by rubber wood (Hevea brasiliensis), and gymnosperms, represented by Douglas fir (Pseudotsuga menziesii) and Canadian trembling aspen are shown in Table 11. Date palm stem fibers are longer than those of aspen fibers and comparable in length to fibers from rubber wood but are shorter than those of Douglas fir.

Table 11. Fiber dimensions of date palm wood in comparison to rubber wood, Douglas fir and aspen fibers

Fiber dimension	**[1]Date palm wood**	**Oil palm wood**			**[2]Rubber wood**	**[3]Douglas fir**	**[4]Aspen fiber**
		2 m	6 m	10 m			
Length (mm)	1.34	2.08	2.09	2.00	1.40	3.40	0.96
Diameter (µm)	40.7	29.2	26.6	22.5	31.30	40.00	20.8
Cell wall thickness	6	8.08	6.05	6.3	5.0	n.a	n.a

1 – Mahdavi et al. (2010), 2 - Khoo Kean Choon (per. Comm. 1990), 3 - Mohamad et al. (1985), 4 - Law et al. (2007)

No detailed literature was found about the physical properties or fiber dimension of date palm wood.

2.3.2.3 Mechanical properties of date palm wood

As other monocotyledons, it is assumed that the mechanical properties of the date palm trunk wood show certain variability within the trunk, in radial and vertical direction. Shamsi and Mazloumzadeh (2009) investigated several important physical and mechanical properties of date palm trunk in green/fresh condition. The aim of their work was to evaluate the mechanical behavior of the tree trunk and to use this information for mechanical pruning and fruit harvesting in the plantations. The data are shown in Table 12. It is important that the fibers are positioned in longitudinal direction and mostly parallel to each other for the whole length of the tree trunk. They found low values for longitudinal shear strength but quite normal values for tension and compression strength parallel compared to other palms or wood species.

Table 12. Strength test results for date palm trunks (wet conditions) (Shamsi and Mazloumzadeh 2009)

Properties	**Tree trunk**
Average compressive strength in radial direction (r σ), MPa	3.0
Average shear strength in longitudinal direction (lτ), MPa	1.1
Average tensile strength in longitudinal direction (t σ), MPa	60.0
Average compressive strength in longitudinal direction (c σ), MPa	5.3

The mechanical properties findings can be used as a knowledge basis for a wide range of applications such as furniture and composites industries. Tufashi (2013) studied some mechanical properties of date palm wood and specifically focused on the shear strength and glue-line strength. The shear values tested along the stem height of date palm were compared with oil palm and other common species such as larch, pine, beech and oak. Compared to larch 8.82 N/mm², pine 9.80 N/mm², beech 15.69 N/mm² and oak 7.84 N/mm² the date palm wood showed low values (Table 13). But shear strength of date palm wood was comparable to oil palm wood.

Table 13. Average shear strength of the date palm wood, oil palm wood, larch, pine, beech and oak (Tufashi 2013)

	Date palm stem			**Oil palm stem**			**Larch**	**Pine**	**Beech**	**Oak**
	Base	Middle	Top	Base	Middle	Top				
Shear strength (N/mm²)	2.89	1.41	1.32	3.27	1.89	1.18	8.82	9.80	15.69	7.84

Further, based on the average the glue-line strength values of the date palm stem, Tufashi (2013) stated that the shear strength of the glue-line in the date palm shows no clear trends. An increase in shear strength glue-line can be seen in all stem heights from the IZ towards the CZ. Over the stem height from the base to the top the averaged results of the glue-line shear strength shows a small decrease. The test results are summarized in Table 14.

Table 14. The glue-line strength of date palm wood (Tufashi 2013).

Date palm	**PZ (N/mm^2)**	**CZ (N/mm^2)**	**IZ (N/mm^2)**
Base	1.51	1.45	0.81
Middle	0.79	1.25	0.98
Top	0.88	1.04	0.82

According to results in Table 8 (Killmann and Lim 1985) bending strength values of the date palm trunk (11-23 MPa) are generally weak compared to other timber species. They are also hardly comparable to coconut (26-105 MPa) but in the similar range as oil palm wood (8-45 MPa). Variations in compression strength parallel to grain also follow the same trend as the bending strength. The hardness value of date palm stem (2000 N) was generally lower than most timber species including rubber wood (4320 N) as well as coconut wood (4400 N). The hardness of the date palm wood (2000 N) was, however, comparable to that of Norway spruce (2140 N), poplar wood (2500 N) and oil palm wood (2450 N). Especially for hardness, the density of wood plays an important role.

For date palm wood, the results on mechanical properties, thermal conductivity and moisture diffusion into composite are satisfying in order to develop a future insulating material for building construction (Al-Juruf et al. 1988; Al-Sulaiman 2002; Abu-Sharkh and Hamid 2004; Kahraman et al. 2005; Kriker et al. 2005; Kahraman and Abu-Sharkh 2007; Sbiai et al. 2008). Similarly to the references (Khedari et al. 2001; Khedari et al. 2005; Asasutjarit et al. 2007) which discussed the development of cement blocks and lightweight cement boards using coconut palm products, the date palm wood will be a good candidate for the development of efficient and safe insulating materials (Agoudjil 2011).

No more references in the literature were found regarding the mechanical properties of date palm stem wood.

2.3.2.4 Chemical properties of date palm wood

Hindi et al. (2010) investigated the physicochemical characterization of date palm wood fibers and compared them with to the other lignocellulosic natural resources such as Conocorpus erectus, Leucaena leucocephala, Simmondsia chinensis, Azadirachta indica and Moringa peregrine. The main findings are shown in Table 15.

The highest total extractives content for date palm surface fibers may be attributed to the open anatomical structure which is easily accessible for the chemicals (Khristova et al. 2005).

It can be seen from Table 15 that the surface fibers from the date palm have higher contents of lignin (31.3%) but lower contents of holocellulose compared to the other woody materials. Low lignin content of a lignocellulosic material reduces pulping time and chemical charge compared to those of other non-wood raw materials (Lopez et al. 2008; Diaz et al. 2007). The date palm surface fiber contained higher ash than the other resources (Table15) which has a negative effect on the chemical recovery process (Khiari et al. 2010) and is negative for mechanical processing as well.

Table 15. Mean values of total extractives, lignin, holocellulose and ash contents of some Saudi lignocellulosic natural resources (Hindi et al. 2010).

Lignocellulosic material	**Total extractives content (%)**	**Lignin content (%)**	**Holocellulose (%)**	**Ash content (%)**
Phoenix dactylifera surface fibers	16.44	31.30	40.31	11.82
Conocorpus erectus wood	12.93	28.83	57.68	0.91
Leucaena leucocephala wood	9.74	18.86	70.82	1.22
Simmondsia chinensis wood	15.08	28.18	53.11	2.31
Azadirachta indica wood	10.23	27.94	59.91	1.47
Moringa peregrine wood	8.52	28.26	59.64	2.73

Tufashi (2013) studied several chemical parameters of date palm wood such as pH value, buffer capacity, ash and silica content. Buffer and pH-value influence gluing and surface treatment behavior as well as corrosion of metals. Ash and silica influence the machining of wood. The results of testing along the stem height of date palm compared to some other native wood species such as larch, pine, beech, and oak. Table 16 shows his main results. He found a higher pH-value but similar buffer capacity for date palm wood compared to common timbers. Both properties should not have a big influence on gluing properties. Generally, gluing tests with PVAc, UF and MUF glues have shown no severe problems if hardeners and buffers of the glue are well adjusted. The porous structure of the parenchyma tissue requires some 10-30% higher glue application compared with normal hardwoods and softwoods. The ash and silica content from date palm wood has higher values than other wood species. Date palm wood showed relatively low silica content compared to other palms (Tufashi 2013). The potential problem of heavy wear on the tools during processing was not so much influenced by ash and silica for date palm but to the vascular bundles density in combination with the parenchyma tissue of low density (Killmann 1993).

Table 16. Chemical properties of the wood from date palm, larch, pine, beech and oak (Tufashi 2013)

Chemical composition	**Date palm stem**			**Larch**	**Pine**	**Beech**	**Oak**
	Base	Middle	Top				
PH	5.4	4.6	5.4	3.6	3.4	3.3	3.4
Ash (%)	1.75	2.28	2.32	0.27	0.26	0.55	0.51
Silica (%)	0.08	0.16	0.25	0.01	0.04	0.03	0.01
Buffer mol/l	6.47	6.51	8.09				

3. Uses of palm wood

The use of palm timber has a certain tradition for coconut wood because it is of higher density and strength compared to other palm species and it grows in rural areas where local timber has a high importance. For oil palm and date palm, no semi-industrial or in industrial use exists yet. The main reasons are: the fact that the properties are less known and appropriate processing technologies are missing, the properties are lower compared to timbers already on the market and -for oil palm- while now there is enough timber supply with other species. Considering the overall situation in the respective countries and the palm wood properties, the following utilization strategies has some future potential:

3.1 Coconut palm

Technically, the stems of coconut trees can be converted into a number of products such as:
- building poles and posts transmission poles,
- sawn timber: sawn timber of coconut palm can be used economically (1) at village level, (2) in areas where conventional timber is in short supply and/or expensive, (3) for selected products,
- building purposes, furniture, flooring and packaging,
- pulp and paper,
- particleboard,
- charcoal and others.

However, economic considerations reduce the utilization options considerably.

The performance of coconut wood in industrial uses construction and housing is closely related to its physical/mechanical properties and anatomical characteristics (Mitchell 1964; Gurfinkel 1973). The physical properties of coconut wood depend on the density, moisture content and shrinkage. Base on density, grading methods can be developed to determine the physical and mechanical properties (Frühwald et al. 1992).

For load bearing structures HD/MD coconut wood showed quite good properties, the grading of wooden elements (gluelam and cross laminated timber) causede no problems (Hasemann 2012). Non load bearing uses like roof, wall and floor elements are possible with MD coconut wood. All density classes from coconut wood are suitable for furniture and interior and decoration. However, the coconut trees require 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 (Kilmann 1988).

Due of the drawbacks of at least MD/LD density, coconut wood has a low natural durability. This is not a serious problem for dry interior use, but a major problem for exterior use. Appropriate wood preservation is necessary (Frühwald et al. 1992).

3.2 Oil palm

A part from the fruits the oil palm traditionally has many uses. Its trunk and leaves are used in home construction.

The fruits of the palm have been used for a long time for the production of oils. The oil obtained from the seeds of palm has very high quality as cooking oil since it does not contain any free fatty acids (Perfect 2013). Other traditional uses for the extracted oils are for candles and soap production. The residue remaining after the pressing of the fruit is due to its high protein content, suitable as a concentrate for foods and is still used today for this purpose.

The shells of the seeds may be used as fuel (Maydell 1968).

Oil palm trunk biomass waste is collected during replanting, when trees exceeding the economical age are felled (Yuliansyah et al. 2009). From the study by Lim and Khoo (1986), the oil palm contains a large proportion of soft material. The hard to medium material occupy only about 20% of the total area of the cross section. From these observations and the preliminary results obtained, the authors argue that oil palm trunks can be used as lumber, pulp and paper-producing materials, reconstituted boards and bio-composites. The oil palm wood may provide a good source of fiber material for the pulp and paper industry. Results indicated that fairly good paper can be produced from the oil palm stem (Mohd. Nor et al. 1985). Oil palm trunk has also been utilized as raw material in the production of panel products such as particleboard (Teck and Ong 1985), medium density fiberboard (MDF), mineral-bonded particleboard, block board (Choon et al. 19991) and cement board (Schwarz 1985). Novelty items such as handles, ash trays, lampshades, paper weights, pencil and calling card holders and cigar boxes can also be manufactured by using only the medium and hard portions of the stem. Oil palm trunk can also be used in laminated products such as laminated veneer lumber (LVL) and both interior and exterior plywood (Nordin et al. 2004; Sulaiman et al. 2008). The utilization of oil palm trunk also reduces the dependency on industrial raw materials from tropical forests.

Commercial production of oil palm lumber has been shown to be viable but its acceptance in the market is limited because of its perceived poor machining properties due to the presence of high amounts of silica and variable density (Killman and Lim 1985). Ratnasingam et al. (2008) reported that oil palm lumber can be successfully manufactured using high cutting speeds.

On the other hand, oil palm wood has a number of drawbacks such as strength, durability and mechanical properties. It was reported by Baker et al. (1998, 1999a;b) that the dimensional stability of the oil palm trunk has very low values with variations of shrinkage in the range of 9.2 to 74%. A value of 74% is certainly not caused by normal shrinkage but is possible for volume reduction due to cell collapse during drying. The strength is in the class III-V and the durability falls in class V. These results indicate that only 1/3 to 3/4 of the outside part of the bottom of the oil palm trunk has better physical and mechanical properties. It could be used as lightweight building as well as furniture construction materials (Dungani et al. 2013). Sadikin (1986) stated that the oil palm trunk can be used as wood construction until 2/3 from the outer part across the trunk and the other 1/3 part can be used for making house tools. Sadikin (1986) suggested that the utilization of oil palm trunk for construction purposes was better to use 1/3 from outer part of the trunk based on the following reasons:

- The specific gravity of oil palm trunk at peripheral zone was extremely different with the central and inner zone,
- The shrinkage values of oil palm trunk at both central and inner zones was far higher values that peripheral zone.

3.3 Date palm

The date palm has been an important crop in arid and semiarid regions of the world throughout history. It has always played an important part in the economic and social life of the people of these regions.

Date palm terms of use (Al-Gboori and Krepl 2010):

(1) The fruit of date palm (date) as a primary product of the date palm is rich in protein, vitamins and mineral salts and is well-known as a staple food. That is why it represents an essential element of diet for both humans and animals (the low-grade date with kernel). All secondary products of the palm result from annual pruning and have essential uses for the cultivator (El-Mously et al. 1995). No waste results from the growing of palms.

(2) The leaves are important to the production of paper, cartons and glue plates and also the leaves are used for making ropes, cord, baskets, crates and furniture. The base of the leaves

and the fruit stalks are used as fuel.

(3) The coir is used for making washing and bathing sponges as well as for the manufacturing of ropes for different uses. From coir, rope nets and bags for the transportation of agricultural crops on camels are made. Household brooms and fly whiskers are also made from coir.
(4) The spadix stem is crushed to obtain very strong fibers for tying up agricultural crops. The spadix stem ends with fruit stalks are used as brooms. Spadix stems of certain palm species were even used for fire making by rubbing. They were also used as coat hangers, after being sliced into strips, were used for making screens for household use.
(5) The palm trunk is used, after cutting it into halves or quarters as beams to use for ceilings or walls in rural and desert regions (El-Mously 1997). The trunk usually is used to erect rustic houses (roofs). Because it is a wood of poor quality from which no plats can be produced, it often is used for wood veneer or combustion (Al-Gboori and Krepl 2010).

Khiari (2010) sayd that the date palm trunks are used as beams and rafters. Leaves are used as a raw material for many of the rural industries. Furthermore, rachis and leaves can be viewed as sources of reinforcing fibers for polymeric matrices in composite materials. Khristova et al. (2005) found that fibers of the date palm rachis are close to those of hardwoods and the open structure of date palm leaves which is easy for chemical to penetrate makes it possible to obtain strong pulp with soda process.

The wood and leaves provide timber and fabric for houses and fences. Generally HD from date palm has potential for medium and lower loads. HD and MD from date palm are suitable for furniture and interior and decoration. In Egypt, the date palm midribs were successfully used in Mashrabia handicrafts as a substitute for the imported beech wood (El-Mously 1997) and in the core layer of blockboard as a substitute for the imported spruce wood (Picea abies). Three layer particleboards were made of palm midrib as a substitute for casuarina wood (Kandeel et al. 1988; El-Mously 1997). The Center for Development of Small Scale Industries and Local Technologies in Egypt has demonstrated the successful use of date palm fronds for the manufacture of lumber-like product having physical and mechanical properties similar to those for imported wood (El-Mously 1997).

Posts and rafters for huts are fashioned of the wood from the trunk of the date palm though this wood is lighter than that of the coconut. It is soft in the center and not very durable. All left over parts of the trunk are burned for fuel (Morton 1987). Thus, the date palm can be represented an eloquent example of integrated sustainable use of renewable material resources.

4 Material and Methods

This chapter describes the experimental design and provides an overview of studies on the anatomical characteristics and physical and mechanical properties of coconut palm wood from Mexico and Indonesia, oil palm wood from Thailand and date palm wood from Iran. This chapter comprises material preparation, and methodological procedures for the experiments.

4.1 Material

4.1.1 Coconut palm wood

4.1.1.1 Coconut palm wood from Mexico

One disk at a trunk height of 2 m above the base of an approximately 40 year-old coconut tree (Cocos nucifera) was obtained from a plantation in Jalisco, Mexico[1)] (wood from C. nucifera grown in Mexico has properties similar to coconut wood grown in Asia (Guzman 1989; Frühwald et al. 1992)).

The disk was 30 cm in diameter and 14 cm thick, along the grain. It was cut into three sections and marked as shown in Figure 18. In order to avoid fungal colonization, the obtained samples were stored at a temperature of -18°C directly after the sawing process and then transported by air to Hamburg (some 24h without cooling, but packed into insulation material). After arrival in Hamburg, the wood was stored cool again.

[1)] Thanks extended to Professor Dr. Arno Frühwald for collecting the material in Mexico.

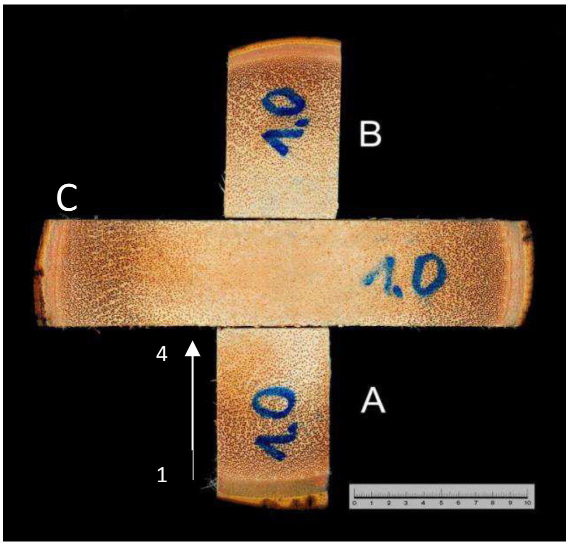
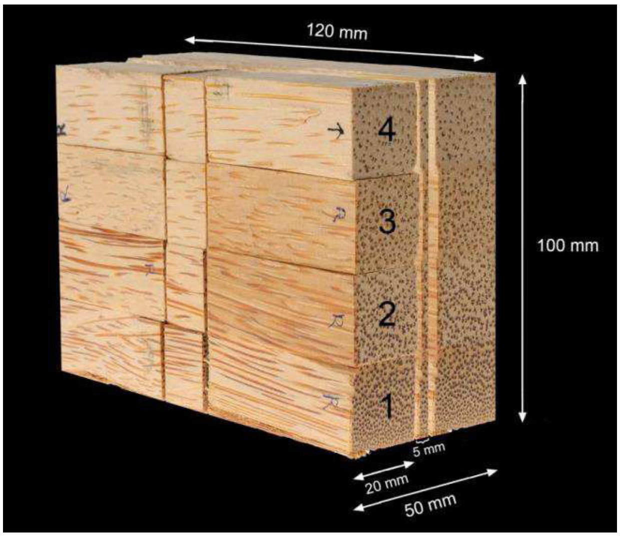


Figure 18. Coconut trunk disk cut into 3 sections (A, B, C)

From the disc, two sections (A, B) were used for anatomical investigations and physical and mechanical properties testing. These sections were pre-cut into four sub-sections 1, 2, 3 and 4 of each 25 mm (tangential)×25 mm (radial)×130 mm (longitudinal) and after drying into pieces of 125 mm in length, 20 mm in width and 20 mm in thickness (Figure 19a). The 125 mm pieces were cut into three test specimens as shown in Figure 19b.



A

Figure 19a. Cutting pattern of section A

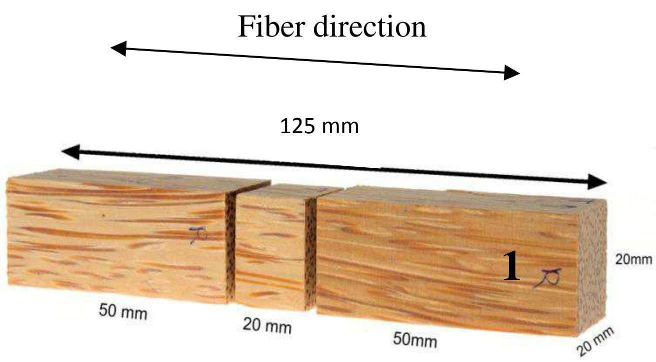


Figure 19b. Cutting pattern of parts 1-4 from section A

The center part with 125 mm in length, 100 mm in width and 5 mm in thickness (Figure 19a) was used to extract vascular bundles. The remaining part was stored in the deep-freezer. As shown in Figure 19b, the bigger parts (50×20×20 mm^3) were used lengthwise for compression tests and the middle part (20×20×20 mm³) was used for anatomical and physical tests. The specimen dimension for physical and mechanical properties evaluation followed the DIN standards, 52183/52185.

Details of the wood specimen including properties tested, standards for testing, number of specimen and size of specimen, and from which part of the trunk that the specimen were made, are given in Table 17.

Table 17. Specimen taken from coconut palm trunk (Mexico)

Wood properties	Trunk height (m)	Wood zones	Replication	DIN standard for testing	Specimen dimension (mm)	Number of specimen
Anatomical properties						
Number of vascular bundles	2	IZ; CZ; PZ	2		20×20×20	8
Diameter of vascular bundles	2	IZ; CZ; PZ	60 vascular bundles of each replication: 2×60 = 120		20×20×20	60 vascular bundles of each specimen: 8×60 = 480
Cross-cut area of single vascular bundles	2	IZ; CZ; PZ	60 vascular bundles of each replication: 2×60 = 480		20×20×20	60 vascular bundles of each specimen: 8×60 = 480
Physical properties						
Density	2	IZ; CZ; PZ	6	DIN 52183	20×20×20 and 20×20×50	24
Mechanical properties						
Vascular bundles tension strength parallel to grain	2	IZ; CZ; PZ	20		5×20×125	80
Wood compression strength parallel to grain	2	IZ; CZ; PZ	4	DIN 52185	20×20×50	16

4.1.1.2 Coconut palm wood from Indonesia

The material used is a mix of lumber pieces from about 10 trees harvested in a 40-50 year old plantation in Northern Sulawesi /Indonesia. The lumber was processed and kiln dried in Indonesia then delivered to Germany in boards of 1,000×80(100)×26 mm³. Twelve boards were semi-randomly selected out of some 800 boards representing the full range of density (see Table 18).

Table 18. Density of coconut wood lumber pieces from Indonesia used for testing

Board/number	Air-dry density (g/cm³)
1	1.11
2	0.96
3	0.92
4	0.79
5	0.78
6	0.69
7	0.65
8	0.61
9	0.59
10	0.57
11	0.50
12	0.48

The coconut lumber was sorted into three density groups (high, medium and low). Boards for sample preparation were selected randomly from the three density groups.

Figure 20. Sample boards of coconut wood. From left to right: high, medium and low density.

The preparation of the test specimen was carried out according to DIN-standards. The properties tested and the number of specimen for the various properties is indicated in Table 18 and 19. Details of the specimen including wood properties tested, number and size of specimen and location in the trunk are given in Table 19.

Table 19. Specimen taken from coconut palm trunks (Indonesia)

Wood properties	Trunk height (m)	Wood zones	Replication	DIN standard for testing	Specimen dimension (mm)	Number of specimen
Physical properties						
Density of wood	2	IZ; CZ; PZ	4	DIN 52183	20×20×20	40
Density of vascular bundle	2	IZ; CZ; PZ	5		20×20×50	15
Density of parenchyma	2	IZ; CZ; PZ	5		20×20×50	15
Diameter of vascular bundles	2	IZ; CZ; PZ	5		20×20×50	15
Mechanical properties						
Compression strength parallel to grain	2	IZ; CZ; PZ	14	DIN 52185	20×20×50	40
Shear strength parallel to grain	2	IZ; CZ; PZ	40	DIN 52187	50×50×50	118
Tension strength perpendicular to grain	2	IZ; CZ; PZ	42	DIN 68141	50×50×50	124
Tension strength parallel to grain	2	IZ; CZ; PZ	14	DIN 52188	470 in Length	40

4.1.2 Oil palm wood

4.1.2.1 Origin of wood and on-site processing

Two oil palm trees, approx. 25 years old, with a height of 8 and 10.5 meters, respectively, were felled in November 2012 at a plantation in Krabi Province, Thailand. The plant variety was a cross between E. dura and pisifera according to the plantation owners. This is doubted as the sources for that information were not reliable. The cross between the species dura and pisifera would be tenera. The owner only agreed to cut palms that had declining fruit production or none at all anymore (Kurz 2012)[2)]. The palms trunks A and B were about 8 and 10.5 meter high up to the beginning of the leaves, respectively (Figure 21a, b). The palm trunks (A and B) (Figure 21a, b) were cut with a chainsaw into 6 discs of 10 cm thickness and diameter of (A1: 0.38 m, A2: 0.34 m, A3: 0.31 m, B1: 0.47 m, B2: 0.42 m, and B3: 0.38 m) (see Figure 21a, b). All discs from the oil palm were cut from three positions from the tree, namely from the bottom (2 m), from the middle height (5 m) and the top of the stem (7 m)

[2)] Thanks extended to Valentin Kurz for collecting this material in Thailand.

(see Figure 21a, b). The disk was cut into four sections as shown in Figure 21c. In order to avoid fungal attack, the obtained samples were stored directly in a refrigerator as soon as possible (within 12 hours) after sawing and then transported by air to Hamburg.

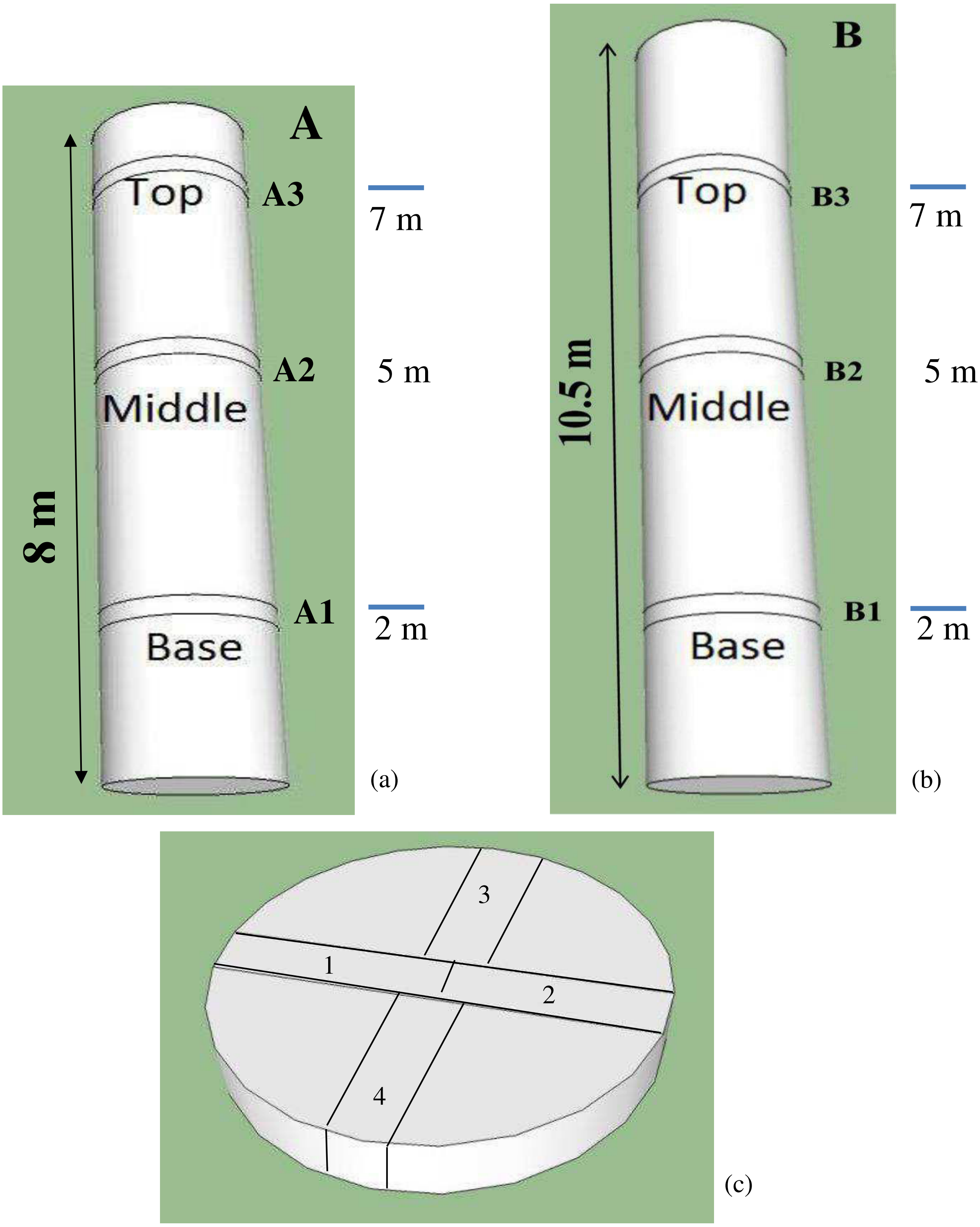


Figure 21. (a, b) Cutting positions of the discs within the oil palm trunks, (c) sketch of one disc

4.1.2.2 Sample processing in laboratory

From each disc, two sections (1, 2) were taken (compare Figure 21c) and used for anatomical investigation, physical and mechanical properties testing. The sections were dried to moisture content (mc) of ~ 12%. A drying schedule based on experience was used with one week in the climate room with 85% RH and 20°C, then for two weeks, in the climate room with 65% RH and 20°C. After drying, sections 1 and 2 in Figure 21c were pre-cut into seven sub-sections 1 to 7 at the bottom of the trunk, six sub-sections 1-6 for the middle part and five sub-sections 1- 5 from the top. Each sub-section was 25 mm (tangential)×25 mm (radial)×55 mm (longitudinal) and after conditioning cut into pieces of 20×20 mm² and 50 mm in length (Figure 22).

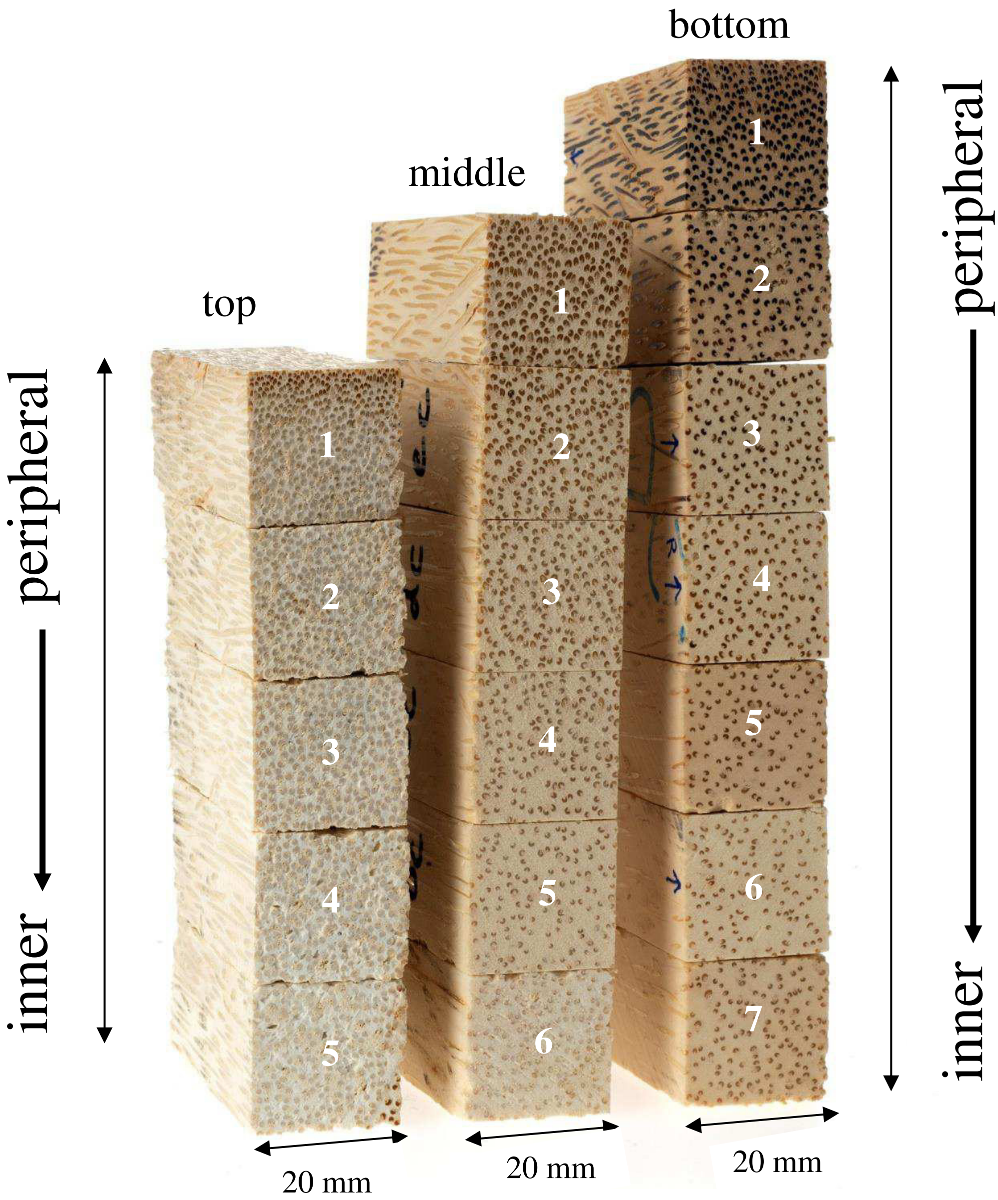


Figure 22. Cutting pattern of section 1 and 2 in Figure 21c

Further, from each disc, six samples measuring 5 mm (tangential)×20 mm (radial)×125 mm (longitudinal) each were taken representing the peripheral, central and inner zones of the disc for preparing individual vascular bundles from the different morphological zones (Figure 23).

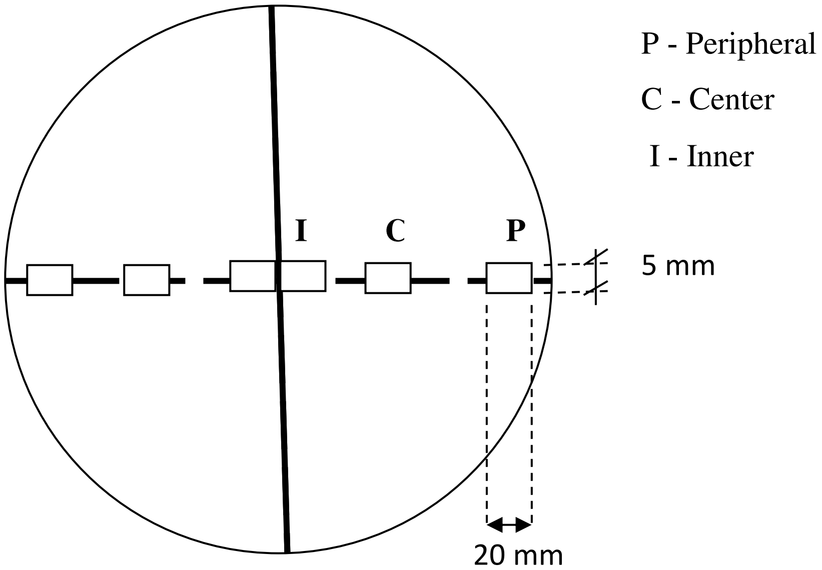


Figure 23. Sketch of the location of samples for vascular bundle preparation within the trunk cross cut area

4.1.2.3 Wood specimen preparation

The preparation of wood specimens from oil palm wood was carried out according to DIN standards. The specimens for anatomical, physical and mechanical properties evaluation were produced according to DIN standards, 52183/52185.

Details of the specimens including type of wood properties testing, standard testing used, number and size of specimen, location within the trunk are given in Table 20.

Table 20. Specimens taken from oil palm trunks

Wood properties	Trunk height (m)	Wood zones	Replication	DIN standard for testing	Specimen dimension (mm)	Number of specimen
Anatomical properties						
Number of vascular bundles	2; 5; 7	IZ; CZ; PZ	8		20×20×20	72
Diameter of vascular bundles	2; 5; 7	IZ; CZ; PZ	60 vascular bundles of each replication: 8×60 = 480		20×20×20	60 vascular bundles of each specimen: 72×60 = 4320
Cross-cut area of single vascular bundles	2; 5; 7	IZ; CZ; PZ	60 vascular bundles of each replication: 8×60 = 480		20×20×20	60 vascular bundles of each specimen: 72×60 = 4320
Physical properties						
Density	2; 5; 7	IZ; CZ; PZ	8	DIN 52183	20×20×20	72
Mechanical properties						
Vascular bundles tension strength parallel to grain	2; 7	IZ; CZ; PZ	12		5×20×125	108
Wood compression strength parallel to grain	2; 5; 7	IZ; CZ; PZ	8	DIN 52185	20×20×50	72

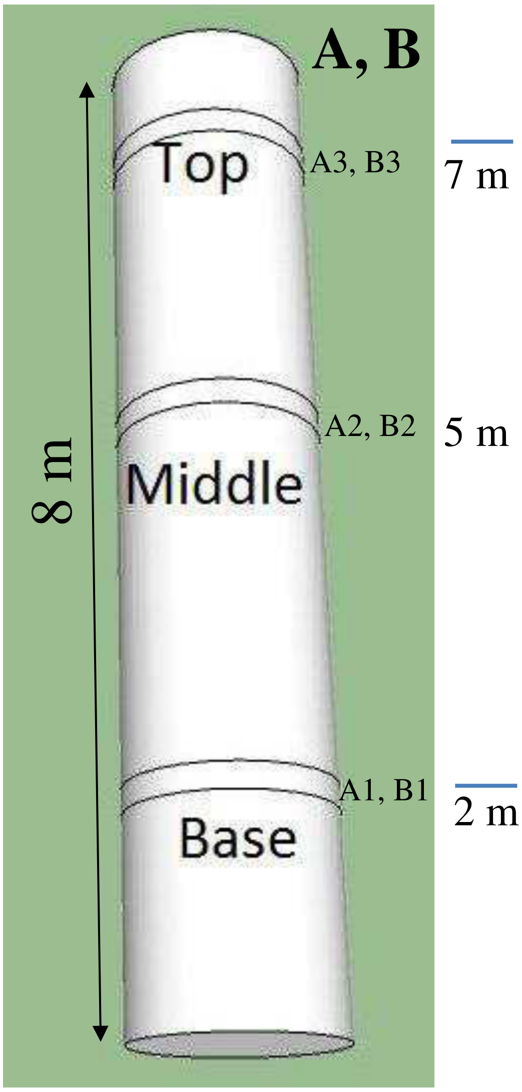
4.1.3 Date palm wood

4.1.3.1 Origin of wood and on-site processing

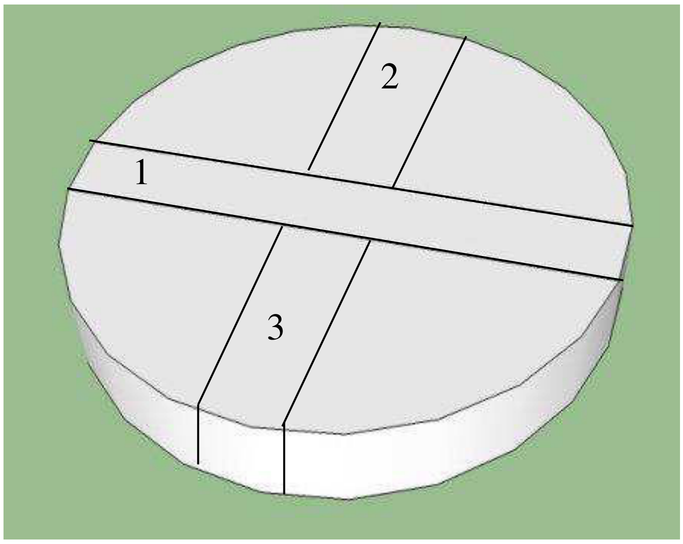
Two date palm trees (Phoenix dactylifera) were felled in January 2013 with a height of 8 meters from a plantation in Khuzestan Province, the Ahvaz countryside in southwest of Iran[3)]. The date palm trees were about 8 meters high up to the beginning the leaves (Figure 24a).

The palm trunks (A and B) (Figure 24a) were cut with a chainsaw into 6 discs of 10-15 cm thickness as shown in Figure 24a. The disk diameter was: A1: 0.44 m, A2: 0.38 m, A3: 0.35 m, B1: 0.47 m, B2: 0.38 m, and B3: 0.35 m. The disks were further cut into three sections as shown in Figure 24b. In order to avoid fungal colonization, the samples were stored directly in a deep freezer (within 12 hours) after sawing and then transported by air to Hamburg.

[3)] Thanks extended to Ali Akrami for collecting the material in Iran.



(a)



(b)

Figure 24. (a) Cutting positions of the discs within the date palm trunks, (b) sketch of one disc.

4.1.3.2 Sample processing in laboratory

From each disc, section 1 was used for anatomical investigation, physical and mechanical properties testing. This section was processed for test specimens in the same way as for oil palm wood (see chapter 4.1.2.2, but with 9, 7, 6 single specimen for the different trunk heights (Figure 25).

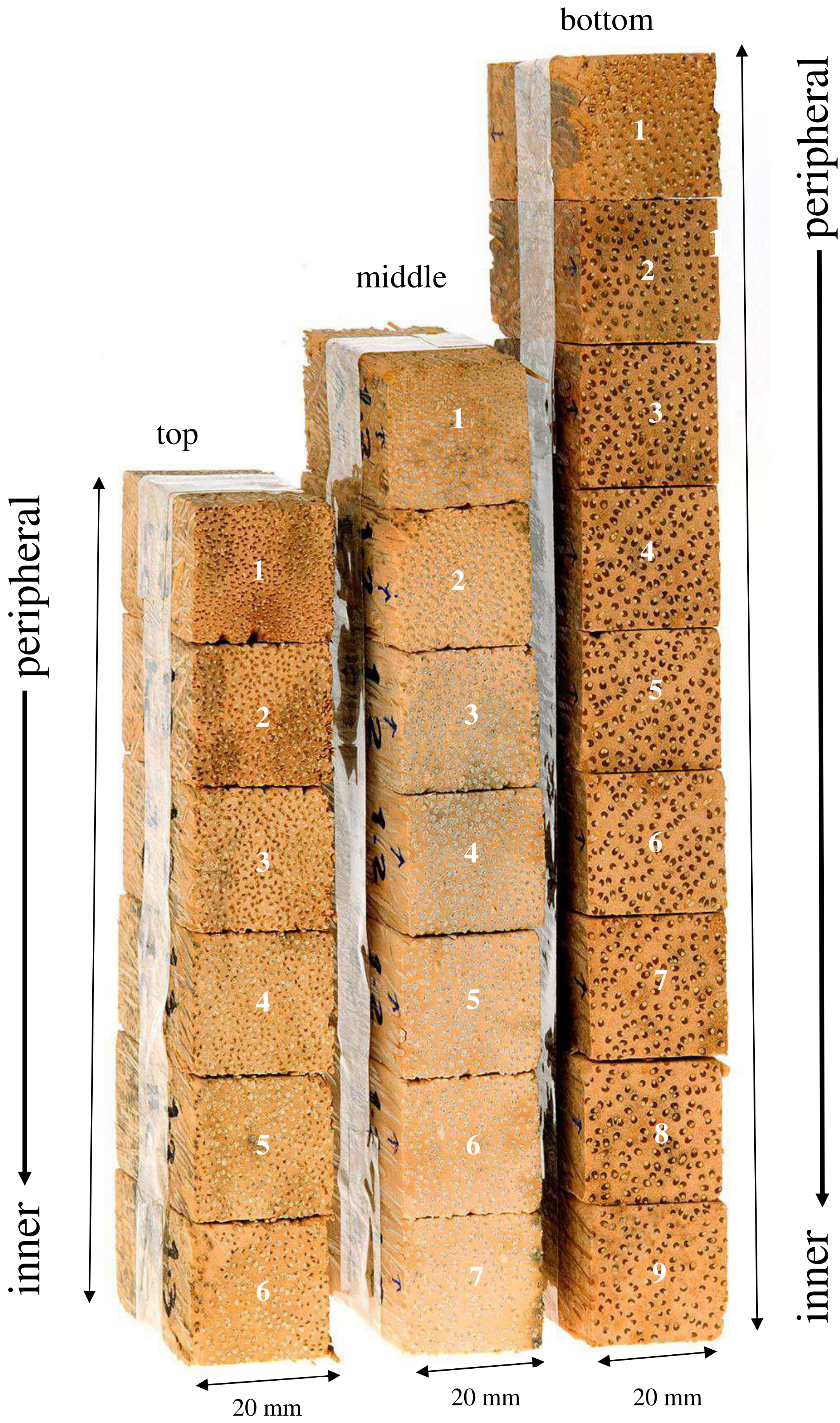


Figure 25. Cutting pattern of section 1 in Figure 24b

Furthermore, from each disc, six samples (5 mm tangential×20 mm radial×125 mm longitudinal) were taken representing the peripheral, central and inner zones of the disc. They were used for preparing individual vascular bundles, similar to oil palm samples as shown in Figure 23.

4.1.3.3 Wood specimen preparation

The preparation of wood specimens from date palm wood was carried out according to DIN-standards.
Details of the wood specimens including type of wood properties tested, DIN-standards, number and size of specimen, and location within the trunk are given in Table 21.

Table 21: Specimens taken from date palm trunks

Wood properties	**Trunk height (m)**	**Wood zones**	**Replication**	**DIN standard for testing**	**Specimen dimension (mm)**	**Number of specimens**
Anatomical properties						
Number of vascular bundles	2; 5; 7	IZ; CZ; PZ	12		20×20×20	88
Diameter of vascular bundles	2; 5; 7	IZ; CZ; PZ	60 vascular bundles of each replication: 12×60 = 720		20×20×20	60 vascular bundles of each specimen: 88×60 = 5280
Cross-cut area of single vascular bundles	2; 5; 7	IZ; CZ; PZ	60 vascular bundles of each replication: 12×60 = 720		20×20×20	60 vascular bundles of each specimen: 88×60 = 5280
Physical properties						
Density	2; 5; 7	IZ; CZ; PZ	12	DIN 52183	20×20×20	88
Mechanical properties						
Vascular bundles tension strength parallel to grain	2; 7	IZ; CZ; PZ	12		5×20×125	108
Wood compression strength parallel to grain	2; 5; 7	IZ; CZ; PZ	12	DIN 52185	20×20×50	88

4.2 Methodology

The methodology is divided into three parts:
(1) anatomical structure of coconut, oil palm and date palm wood
(2) wood properties of coconut, oil palm and date palm
(3) experimental data analysis

4.2.1 Anatomical structure of palm wood

Palm wood characteristics were investigated including anatomical studies based on visual observations using light microscopy, particularly to investigate the wood’s structural elements, such as vascular bundle, vessel and parenchymatous tissue arrangement. In addition wood anatomy, the wood density distribution was investigated due to its import impact on many properties relevant for wood utilization.

The investigation of the wood anatomy was carried out with the help of the Wood Anatomy Laboratory, Section Wood Biology, University of Hamburg and Thünen Institute of Wood Research, Federal Research Institute for Rural Areas, Forestry and Fisheries, Hamburg, Germany.

The anatomical characteristics were determined and measured by light microscopy. The cross-section of specimens used for anatomical characteristics was ($20\times20\times20$ mm^3) (Figure 26a, b). A light microscope equipped with a digital camera (Olympus, SZ H10) was used to take images of the cross-sections. The anatomical parameters (number, cross-cut area and diameter) of vascular bundles are determined using the Cell-F image-software. Since the cross-section of vascular bundles is not perfectly circular, the diameter was measured as shown in Figure 26c.

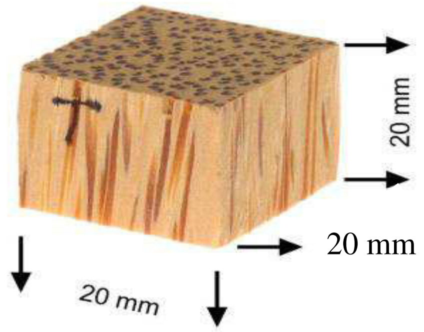


Figure 26a. Sample for density and anatomical tests

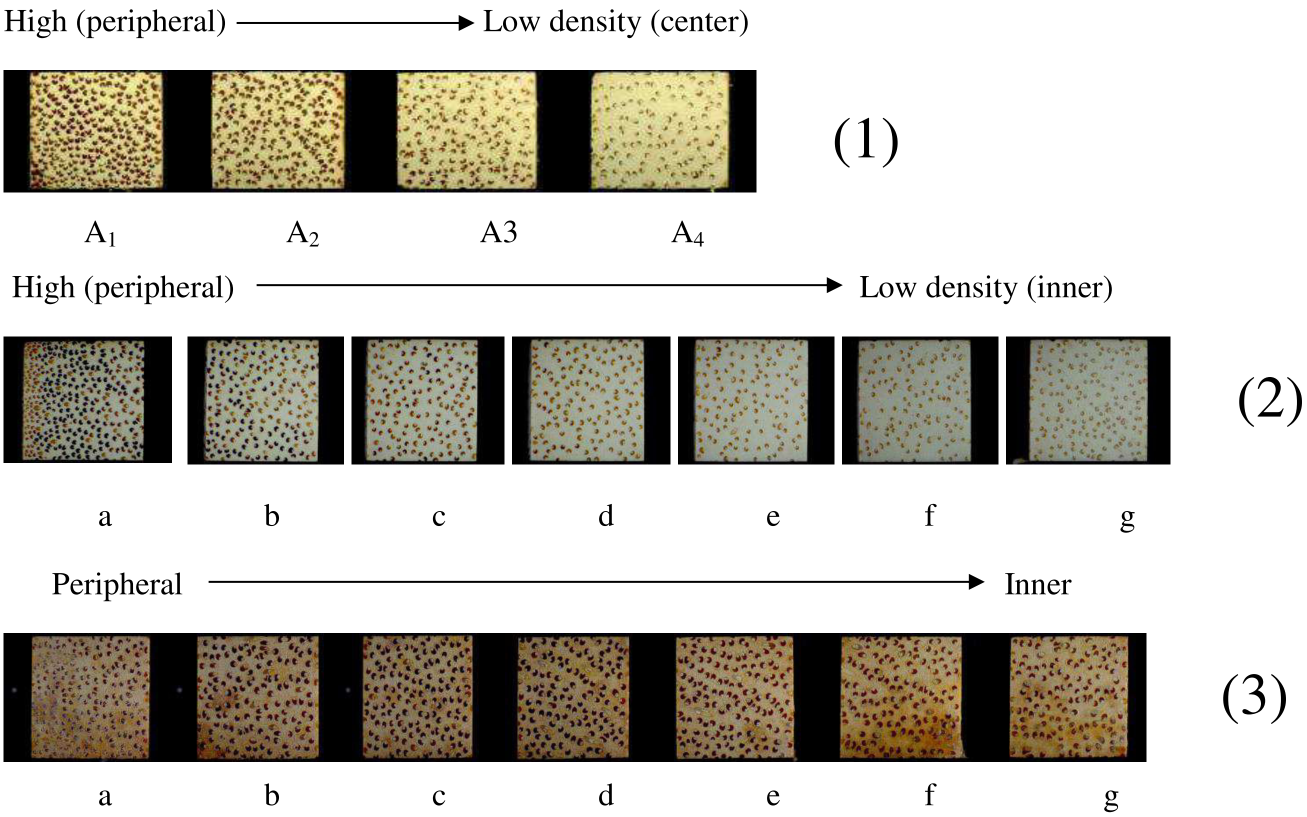


Figure 26b. Wood cross-sections of palm stems: (1) coconut wood, (2) oil palm wood and (3) date palm wood

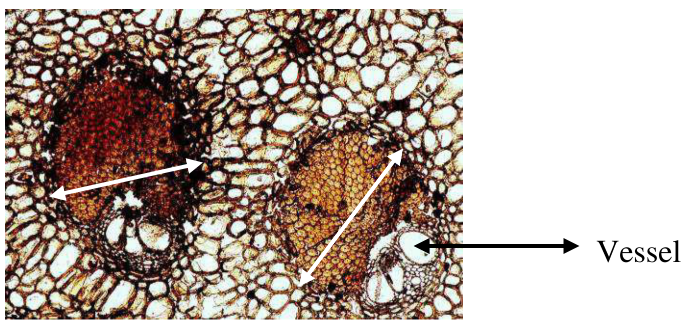


Figure 26c. Vascular bundles

In order to divide the palm trunk material, the disks from the trunks were sawn on the basis of vascular bundles distribution into three zones: peripheral zone (PZ), central zone (CZ) and inner zone (IZ) (Figure 27). The zones were divided between each other according to geometry, meaning that each approximately 1/3 section of the trunk radius was allocated to one of the zones. This is important because according to these three different zones, the features of the palm wood also vary over the stem height and with the transverse distance from the center of the trunk.

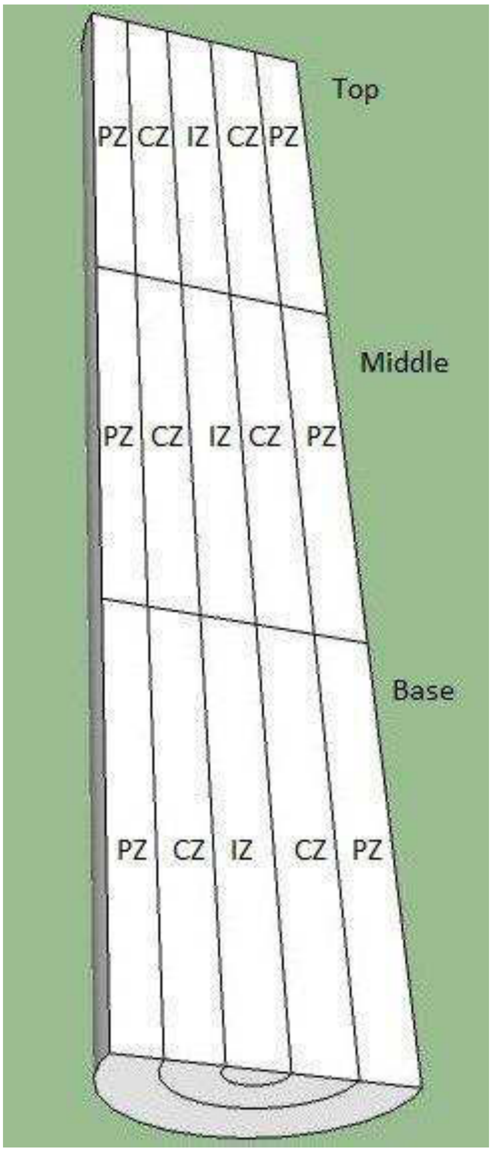


Figure 27. Definition of three wood zones; these zones also represent density classes

4.2.2 Wood properties investigation

Due to the unique wood properties of palms in comparison with common wood species, the following properties were tested and examined based on DIN standards:

Physical properties: 1) wood density, 2) diameter and density of vascular bundles,

Mechanical properties: 1) tension properties of vascular bundles, 2) wood compression strength parallel to grain, 3) wood shear strength parallel to grain, 4) wood tension strength perpendicular to grain, 5) wood tension strength parallel to grain.

The investigations of the physical and mechanical properties are a major subject of this work; they provide the underlying criteria, which explain the potential and technical feasibility of palm wood in the various product areas (solid wood products and wood based panels).

4.2.2.1 Physical properties

Physical properties of palm wood were investigated, including density of wood, diameter, volume, density of vascular bundles, and density of parenchyma.

4.2.2.1.1 Wood density

The density has a significant influence on the properties of wood and therefore it is an important feature for comparison and classification of different types of wood. The density determination is based on DIN 52183 and defined as the relationship of mass to volume. The wood density of palm wood was determined on the basis of air dried specimens. Three stripes along the trunk diameter were taken from 3 heights (bottom, middle and top) of each trunk and then dried in the climate chamber (20°C, 65% RH) to get equilibrium moisture content of ~12%. After drying, the stripes were cut in 20×20×20 mm^3 (Figure 28a). The samples were measured with a digital caliper (Figure 28b) and weighted with a digital scale (Figure 28b).

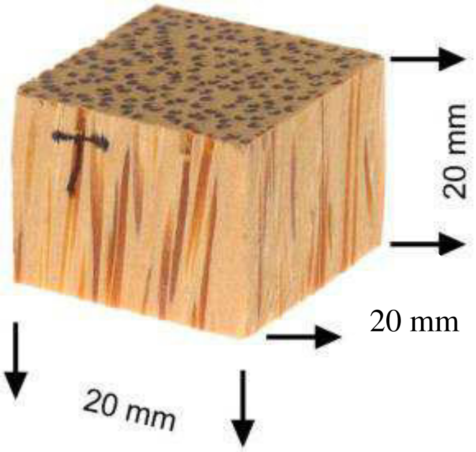


Figure 28a. Sample for density and anatomical tests

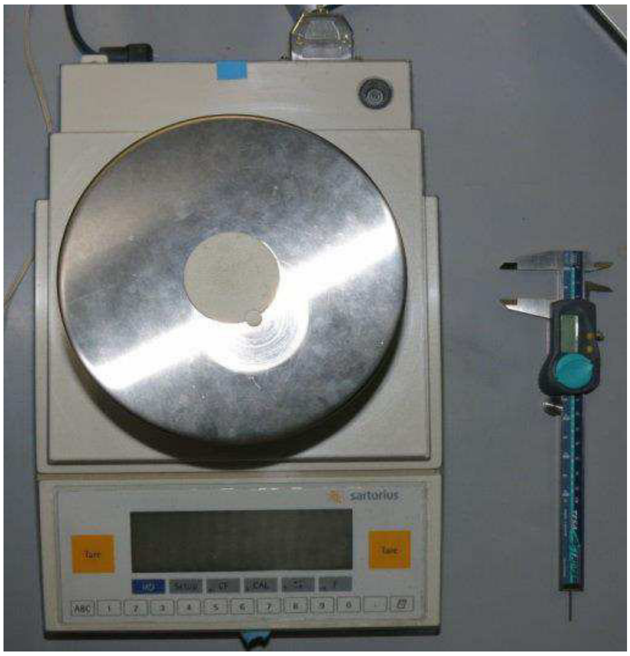


Figure 28b. Digital scale and digital caliper

4.2.2.1.2 Size and density of vascular bundles

For determination of size (diameter) and density, single vascular bundles were carefully dissected from consecutive radial positions of the selected boards under a stereo microscope. Once the surrounding parenchyma tissue was totally removed, the vascular bundles were kept straight throughout the drying process (Figure 29). In total, 15 vascular bundles were prepared from boards 1, 4, 8 (five from each board, see Table 20).

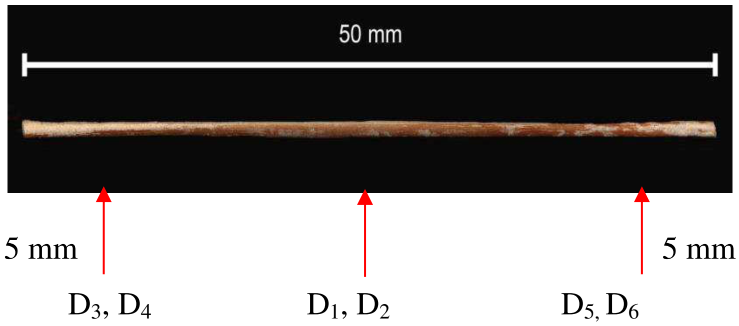


Figure 29. Single vascular bundle for mechanical testing, $D_1 \ldots D_6$ = diameter measurement points.

The vascular bundle diameter was measured with a digital caliper at a precision of 0.01 mm at three points along the length and with two diameters each. These six measurement values were used to calculate the cross-cut area and total volume. The vascular bundles (fiber caps) are not circular in cross-section. But the measuring error for the cross-cut section is less than 3% (repeated measurements) and for the volume between 3-5%. Figures 30a (cross section of high density coconut palm stem) and 30b, c show the different shape of vascular bundles of the cross section. Figure 30b, c shows how the cross-cut area of each vascular bundle was measured.

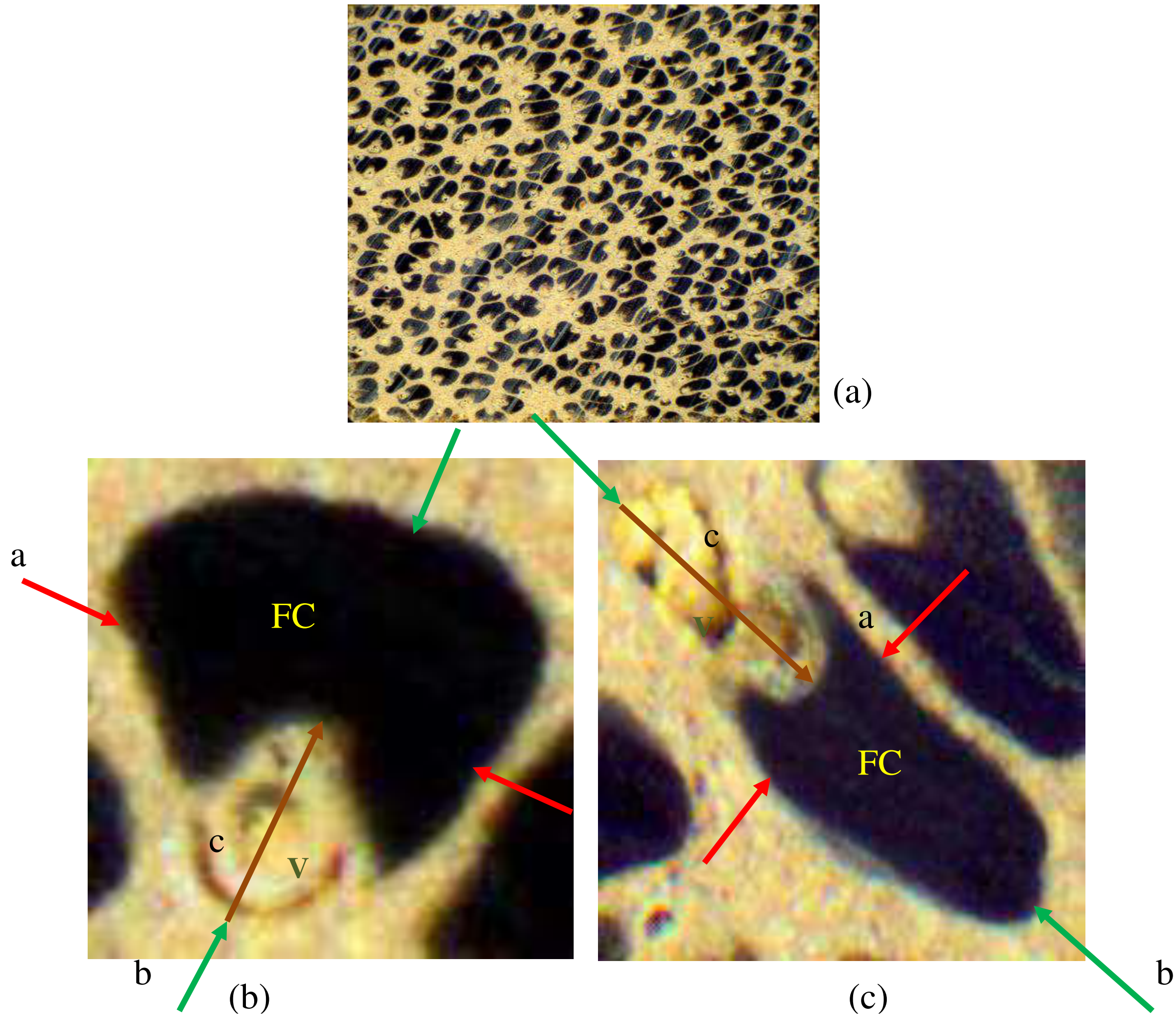


Figure 30. (a) Wood cross section of high density coconut palm stem, (b, c) two different shapes of vascular bundles on the cross section, (Figure b (shape B_1), (Figure c (shape A), V (vessel), and FC (fiber cap)

After cross-cut area determination, each vascular bundle was cut to a length of 50 mm, the weight was taken and the volume and density was calculated. Using the density of wood and the density and number/area of the vascular bundles, it is possible to calculate the average density of parenchyma.

4.2.2.2 Mechanical properties

The following mechanical properties of palm wood were investigated (according to DIN-standards): tensile strength of single vascular bundles, wood compression strength parallel to grain, wood shear strength parallel to grain, wood tension strength parallel and perpendicular to grain. Additionally, for coconut wood from Indonesia the shear strength parallel to grain and wood tension strength parallel and perpendicular to grain was evaluated.

4.2.2.2.1 Tension properties of vascular bundles

For tensile strength testing single vascular bundles were extracted from the wood. The bundle was carefully removed from the wood tissue under a stereo microscope.

The bundles were cut to a length of 50 mm. Two sample holders of aluminum were used and the specimen was glued into the sample holders as shown in Figure 31. A two component glue of epoxy type was used (Uhu® + Plus, endfest 300, 2-K-Epoxidkleber). The sample holders were clamped into a Zwick/Roell universal testing machine equipped with a high resolution 50 KN load cell. The vascular bundle diameters were measured with a digital caliper at a precision of 0.01 mm at three points along the length and with two diameters (see Figure 29). These six measurements were used to calculate the cross-cut area and volume. The vascular bundles (fiber caps) are not circular in cross-section. A minimum of 20 samples was tested in each sample group. All measurements were made at 65% (RH) and 20°C (which leads to an equilibrium moisture content of ~12%). Strain measurements were performed with strain electronic measurement devices clamped to the vascular bundle over a length of 10 mm. The typical tensile stress-strain curves of single vascular bundles are shown in Figure 32.

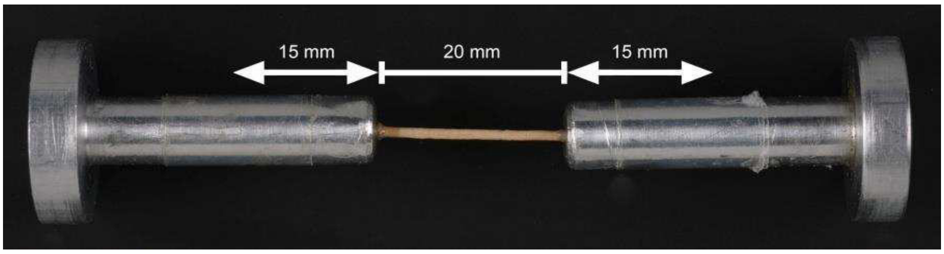
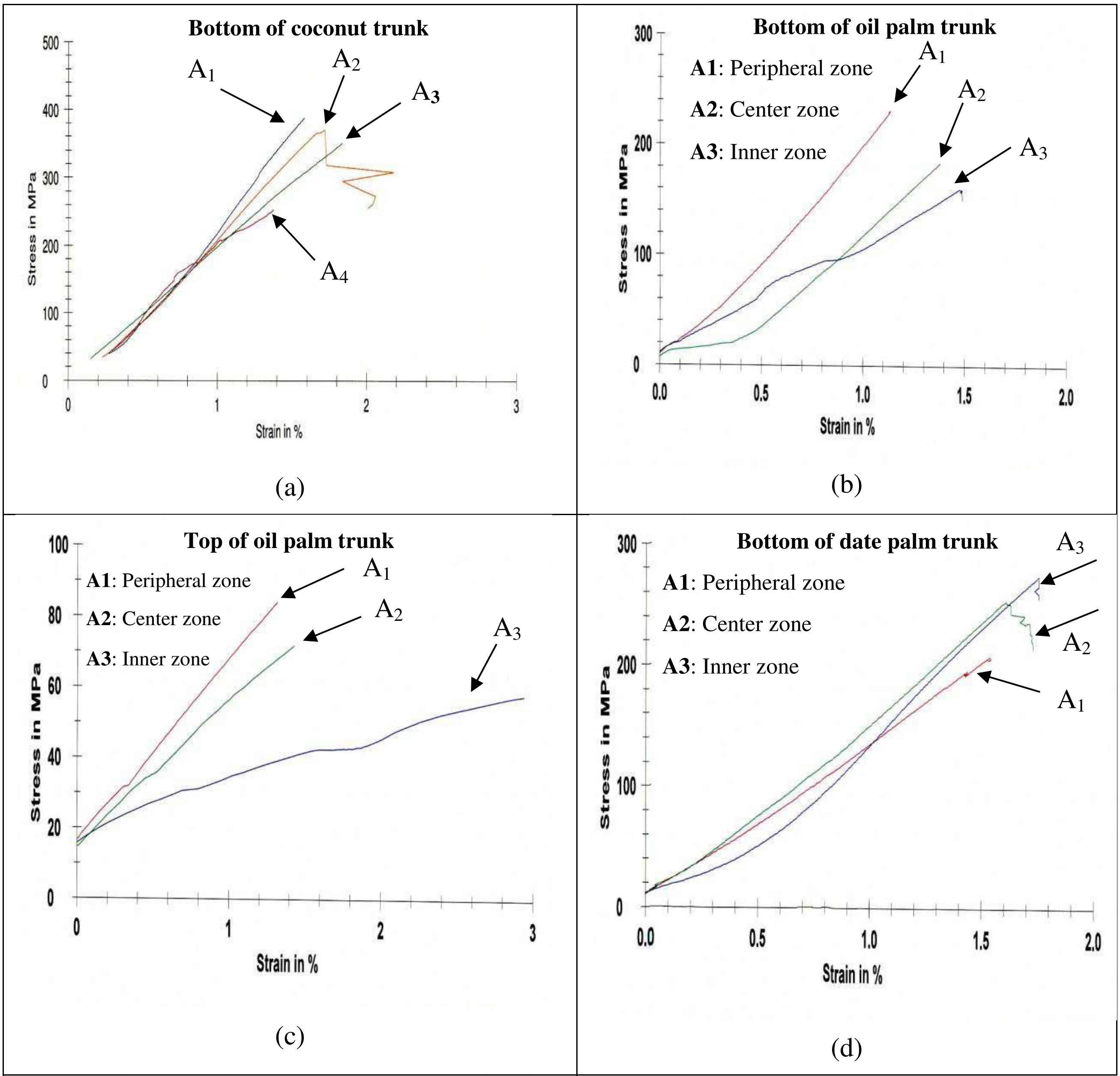


Figure 31. Metal sample holder set-up for tensile testing of single vascular bundles



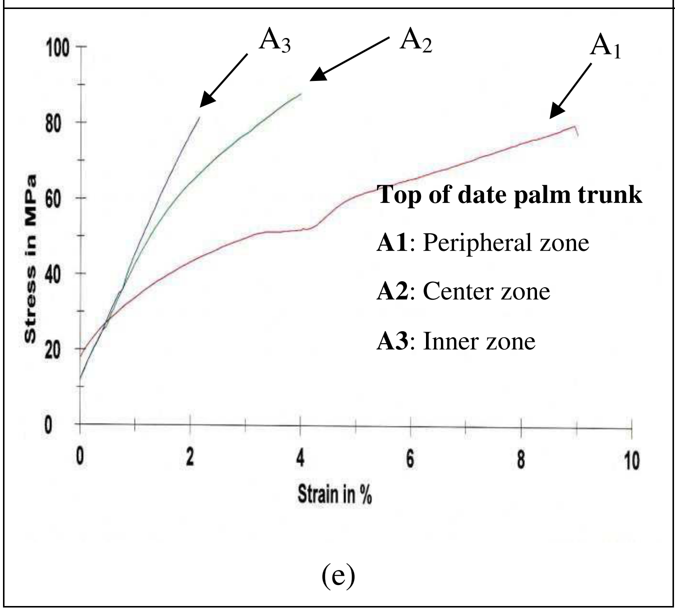
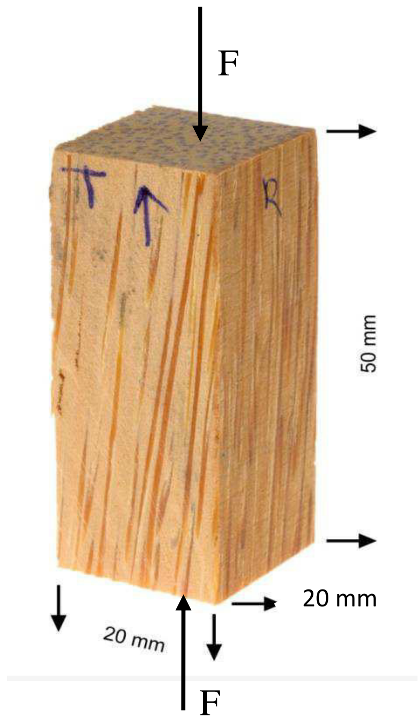


Figure 32. Typical tensile stress-strain curves of single vascular bundles of (a) bottom of coconut trunk (A_1 is near ″the bark″ of the trunk, A_2 and A_3 are between outer and inner layers and A_4 is near the core of the trunk), (b) bottom of oil palm trunk, (c) top of oil palm trunk, (d) bottom of date palm trunk, (e) top of date palm trunk.

4.2.2.2.2 Compression strength parallel to grain

The compression strength parallel to grain including the modulus of elasticity (MOE) and modulus of rupture (MOR) were tested according to DIN 52185 (Figure 33a). The specimen dimensions were measured with a caliper to an accuracy of 0.01 mm. A total of 16 specimens from Mexican coconut wood, 40 from Indonesian coconut wood, 72 from oil palm wood and 88 from date palm wood were tested as shown in Figure 33b.

Special care was taken in applying the compression parallel to grain test specimens by ensuring that the end grain surfaces were parallel to each other and at right angles to the longitudinal axis.



(a)

Figure 33a. Specimen dimensions for compression parallel-to-grain

(b)

Figure 33b. Compression test parallel to grain

4.2.2.2.3 Shear strength parallel to grain

Tests were conducted to determine the parallel to grain shear strength. 118 specimens of Indonesian coconut wood were tested as shown in Figure 34.

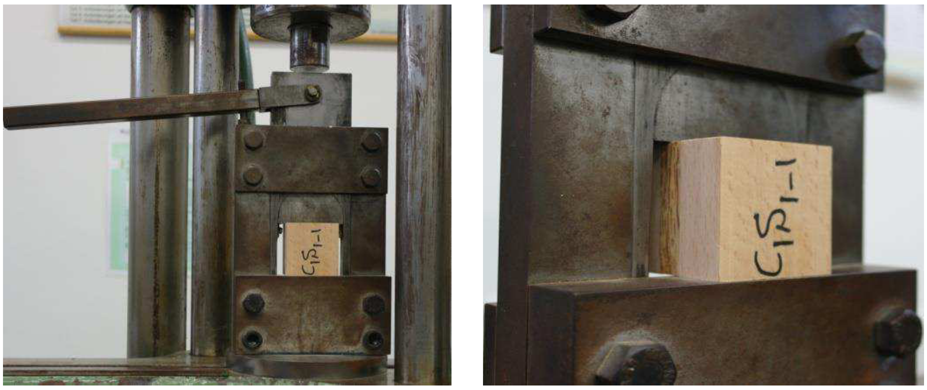


Figure 34. Apparatus to measure shear parallel to grain

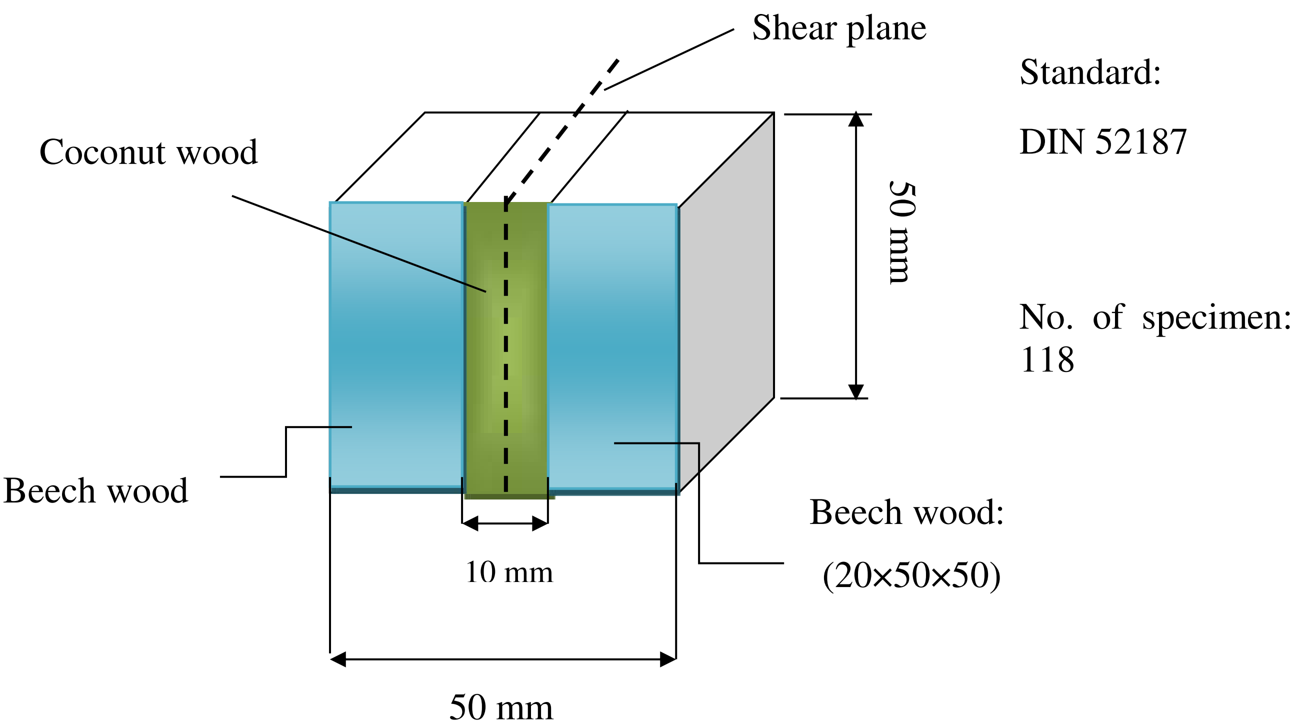


Figure 35. Shear specimen

Measurements

The designated shear area was calculated from the measured dimensions. The shear strength was calculated as the ultimate load divided by area. Testing of the shear block specimens was carried out in accordance with the DIN 52187. The shear took place in the middle of the sample (Figure 35). The testing device is a press in accordance with DIN 51223. The sample is placed into the apparatus in a way so that the fiber direction of the sample matches with the axis of the compression system (Figure 34). The shearing force is uniformly applied so that the maximum load F is achieved within 90 ± 30 seconds.

The shear strength was calculated by the formula:

$$\tau = \frac{\text{F max}}{\text{A}} = \frac{\text{F max}}{\text{a.b}}$$

τ = shear strength [N/mm^2]

F_{max}= maximum force [N]

A = shear plane area of the sample before start of the test [mm^2]

a, b = dimensions of the sample shear plane [mm]

4.2.2.2.4 Tension strength perpendicular to grain

A series of tests were conducted to determine the perpendicular to grain tensile strength of Indonesian coconut wood. In this series, 124 specimens were tested as shown in Figure 36. Specimen design is shown in Figure 37.

The width and length of the designated area of failure were measured using calipers. Tensile strength was calculated as maximum load divided by area.

Figure 36. Apparatus to measure tension perpendicular to grain

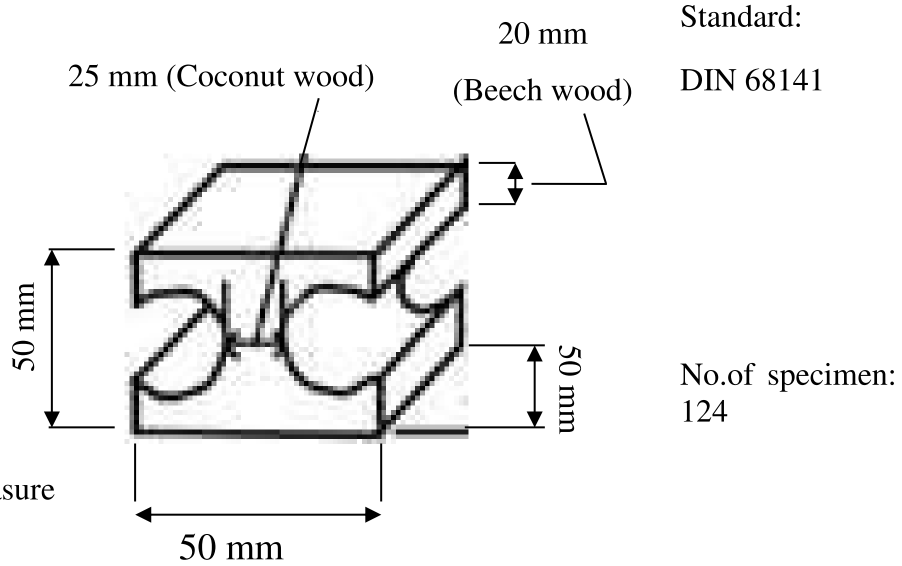


Figure 37. Tension perpendicular to grain test

The specimen cross-cut area was of 25 by 50 mm. The reinforcements for clamping (to avoid bending of the sample) were produced from beech wood (Figure 36).

4.2.2.2.5 Tension strength parallel to grain

Tests were conducted to determine the parallel to grain tensile strength of Indonesian coconut wood. 40 specimens were tested as shown in Figure 38.

A specimen shown in Figure 39 was used. A two side-by-side reinforcement was produced from beech wood. All specimens failed in the middle area.

Figure 38. Apparatus to measure tension parallel to grain

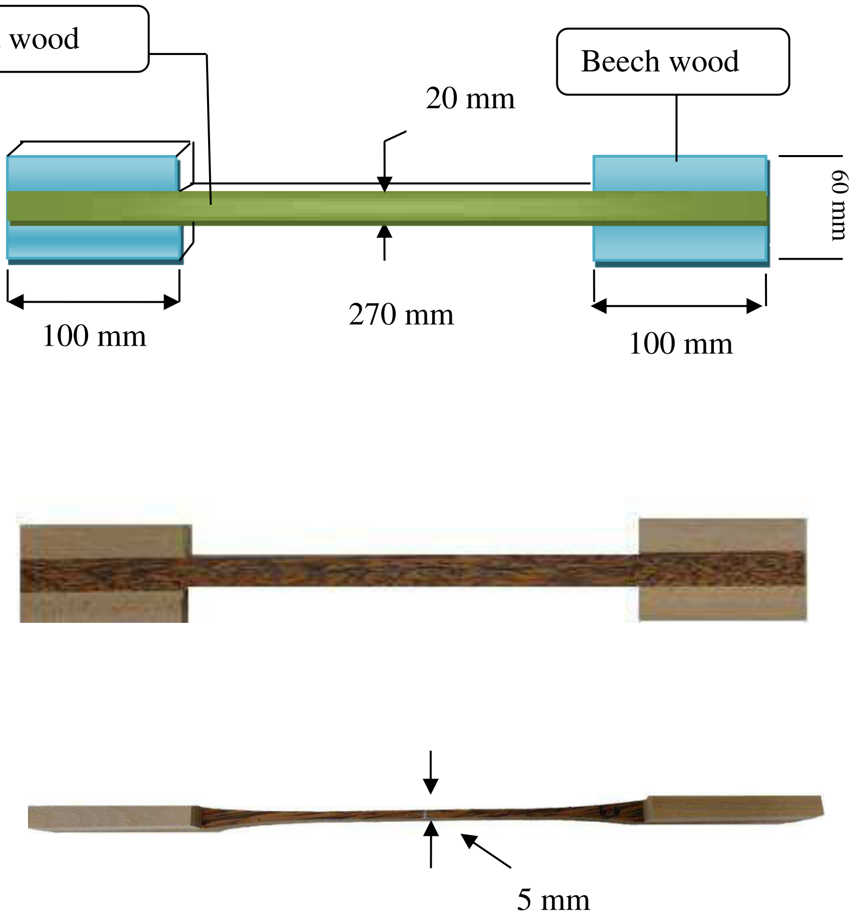


Figure 39. DIN 52 188 specification specimen size and shape

Standard:

DIN 52188

No.of specimen: 40

4.2.3 Experimental data analysis

The experimental data were calculated and analyzed using the statistical data analysis for better interpretation and understanding of the wood properties. The analysis was performed with the statistical program Excel 2010.

The obtained data from anatomical properties of palm wood were analyzed according to the position of every zone from central point to the outer part of the trunk and to define the border line values of each zone on the basis of distribution of vascular bundles. The standard deviation (SD) was used to show the distribution of the data around the mean value. The regression analysis was applied in order to investigate the distribution and relation of palm wood properties (anatomical, physical and mechanical) at different height and trunk cross-cut positions.

5 Results and discussions

The results and discussions are based on visual observation, laboratory tests and analyses, and data analyses using statistical methods for interpretation of the results. This chapter is divided into six sections:

Section 5.1: tension properties of vascular bundles (VB)
Section 5.2: density characteristics of palm wood
Section 5.3: anatomical properties of palm wood
Section 5.4: mechanical properties
Section 5.5: property relationships
Section 5.6: overall discussion and summary

5.1 Tension properties of vascular bundles

5.1.1 Vascular bundle from coconut wood (Mexico) (bottom of trunk)

To investigate the variation of the mechanical properties of vascular bundles (VBs) in the radial direction of the coconut trunk, 20 VBs in each zone (Figure 19a) were separated and tested. The MOR and the MOE were measured according to the description in chapter 4.2.2.2.1. The results are given in Table 22. Figure 40 shows the relationship between relative radius from center and the MOE and the MOR, respectively.

Table 22. Coconut wood (Mexico): Average mechanical properties of vascular bundles (bottom of trunk)

Zones[1)]	No. of VB tested	MOR tension (MPa) average	SD (MPa)	Min value	Max value	MOE tension (MPa) average	SD (MPa)	Min value	Max value
A_1	20	344	60.7	229	452	25144	4545	16491	33430
A_2	20	341	56.8	239	434	23669	3135	17089	30823
A_3	20	327	71.7	211	455	20641	3608	16241	28316
A_4	20	228	69.5	103	351	17636	5465	11451	28937

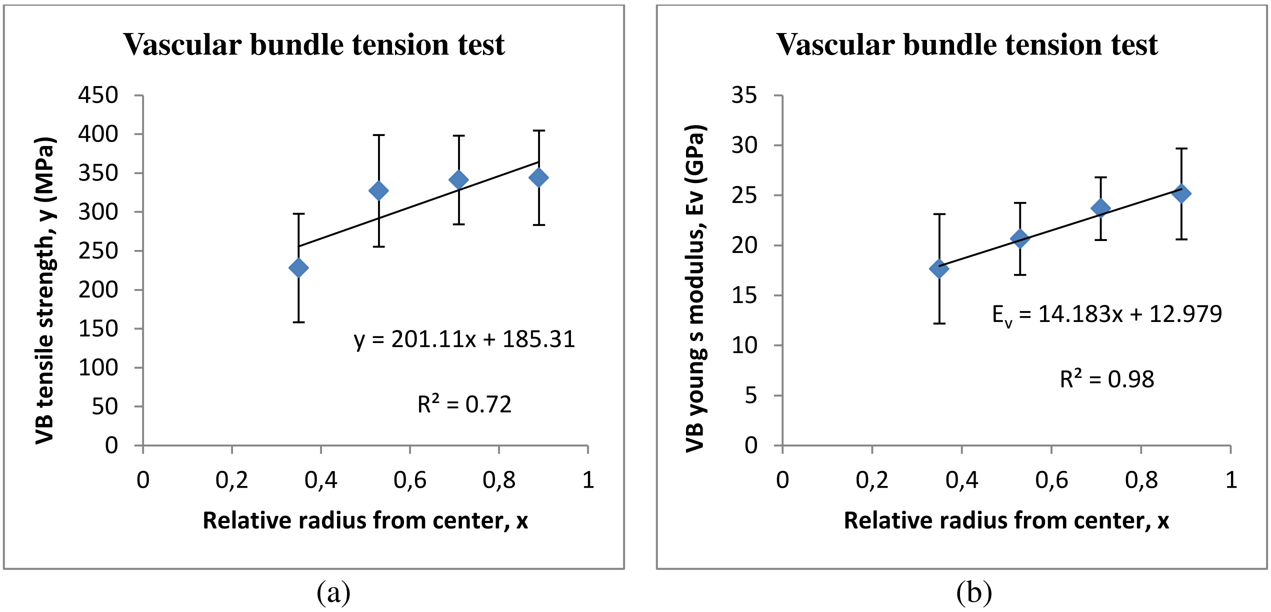


Figure 40. Coconut wood (Mexico): Variation in the mechanical properties of vascular bundles along the radial direction: (a) tensile strength and (b) modulus of elasticity

Obviously the relationship can be described very well by simple linear models. The VB near "the bark" of the trunk shows higher values than those near the trunk core (Figure 40a) and the strength variation for all four subsections can be expressed by the following formula:

$$y = Ax + B$$

where y is the tensile strength of VB and x is the relative radius from the center. Thus, x = 0 corresponds to the trunk radius = 0 and x = 1 to the outer surface of the trunk. The same observation was made with the MOE.

The VBs near the bark of the trunk are stiffer than those near the trunk core (Figure 40b). The correlation between the Young's modulus and relative radius from center is linearly increased as for the tensile strength as well and it can be expressed by the following formula:

$$E_v = ax+b$$

with E_v as Young's modulus of VB.

The MOE and the MOR of VBsare higher in the outer zone compared to the inner zone. This can be related to (a) the anatomy of the VB or the cells (i.e. wall thickness) and (b) lignification. According to the results of Gibson (2012), the concentration of VBs as well as the concentration of fibers within the bundles is greater at 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. Scanning electron micrographs of coconut palm wood in higher magnification indicated that the thicker cell walls have additional secondary layers (Figure 41a, b), which agree with Kuo-Huang et al. (2004). According to Bodig and Jayne (1982), the composition of the cell wall varies through the four layers, with the highest fraction of lignin in the primary layer and the highest fraction of cellulose in the S_2 layers. Based on these results it can be concluded that the VB in the outer part of trunk has additional secondary layers and a higher concentration of cellulose and, therefore, higher tensile strength as compared to the VB in the inner part of the trunk.

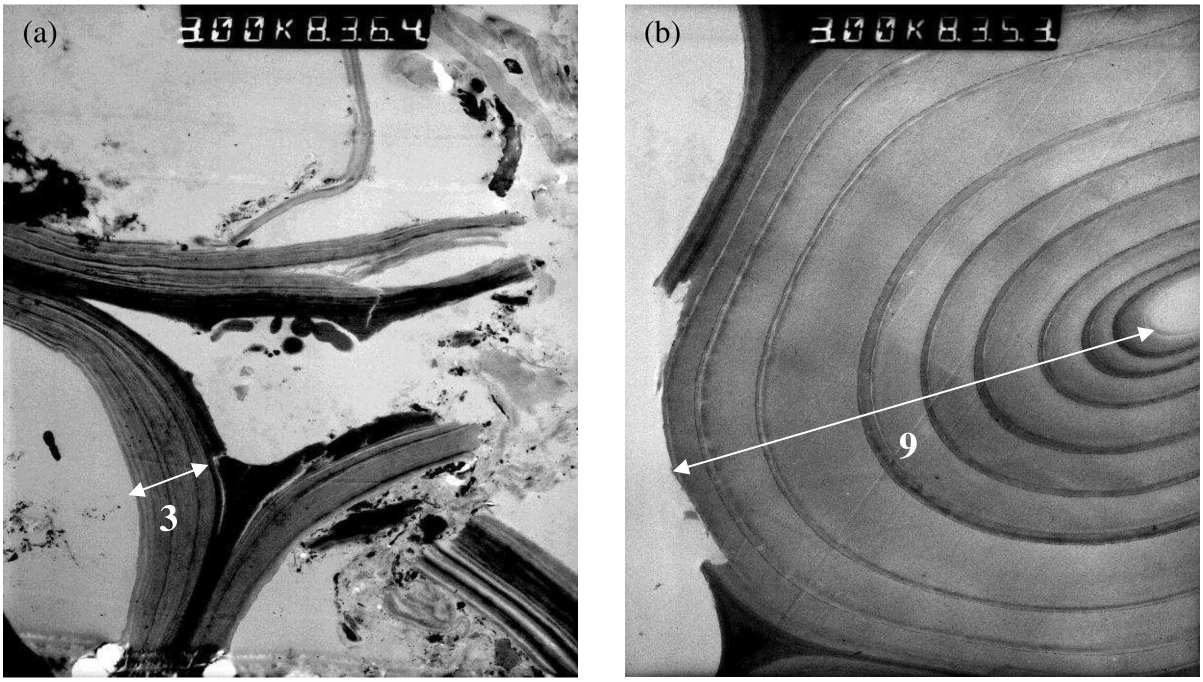
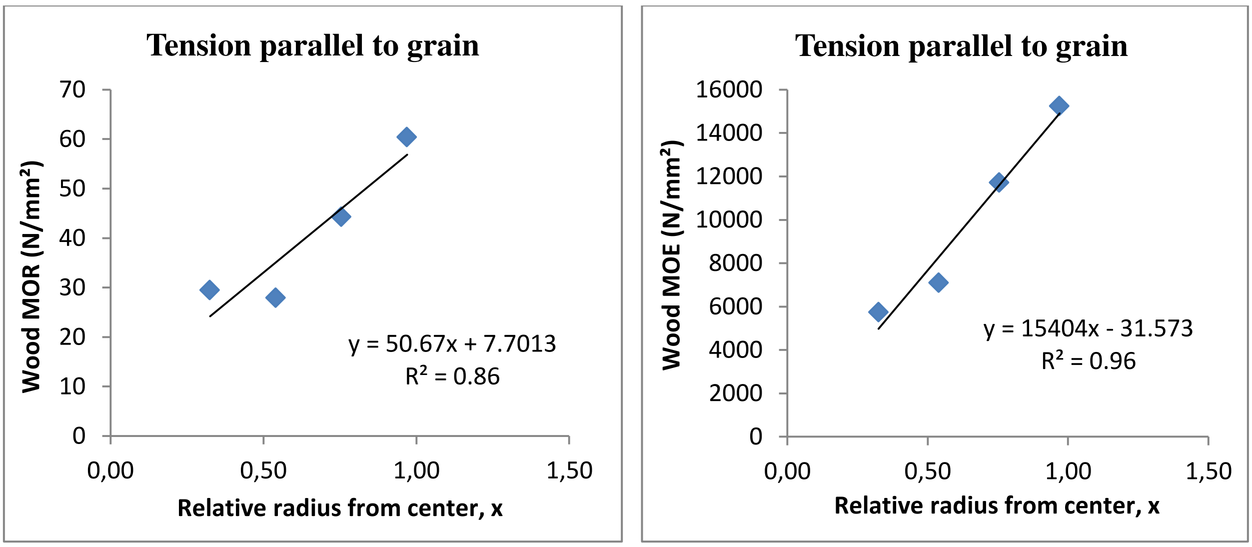
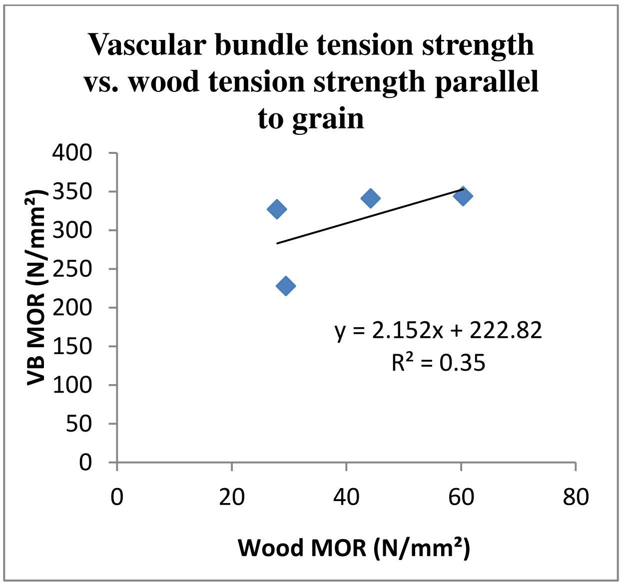


Figure 41. Scanning electron micrographs of cross sections of coconut palm wood showing cells near (a) the center of the stem with a primary cell wall layer and one secondary layer and (b) the periphery of the stem with a primary cell wall and several secondary layers

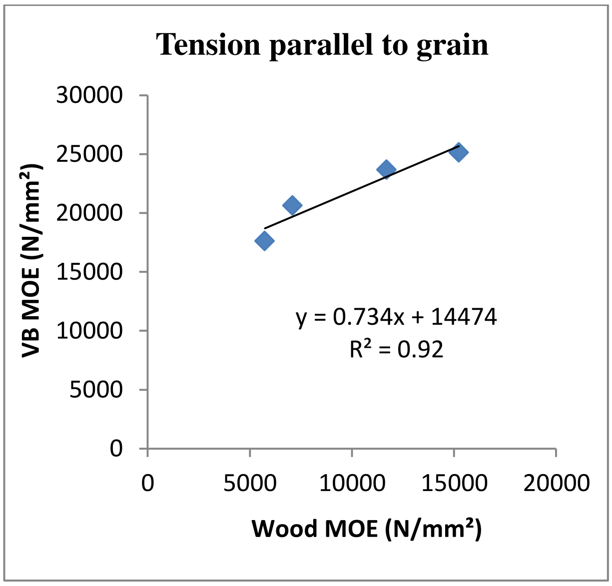
Figures 42a and b show the wood tension properties parallel to the grain properties (MOR/MOE) in the different zones. Figures 42c and d give the relationship between the VBe tension properties (MOR/MOE) and the wood tension parallel to the grain (MOR/MOE). Figure 42e shows the relationship between the wood tension parallel to the grain properties (MOE and MOR).



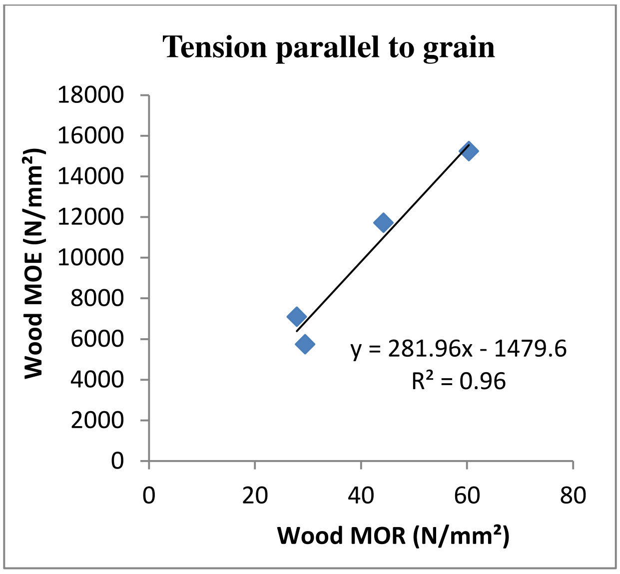
(a) (b)



(c)



(d)



(e)

Figure 42. Coconut (Indonesia): Wood tension MOR/MOE parallel to grain in the different zones (a, b), relationship between the vascular bundle tension properties and the wood tension properties (c, d), relationship between the MOE and the MOR of wood in tension parallel to

From Figure 42, it becomes clear that the single VBs show very high MOE/MOR-values compared to those of wood itself. The correlation between the wood MOR and the relative radius from center follows a linear function. The same observation is made with the MOE. Also there is a strong relationship (R^2=0.96) between the MOR and the MOE in the wood tension parallel to the grain (Figure 42e). These results explain the influence of the VBs on the wood properties.

5.1.2 Vascular bundles from oil palm wood

To investigate the variation of the mechanical properties, the VB from various zones in radial direction of an oil palm trunk, 12 VBs in zones 1, 3, 5 from trunk top and 1, 4, 7 from trunk bottom (Figure 22) were separated and tested. The average values for the MOE and the MOR in tension are shown in Table 23. Figure 43 shows the relationship between the relative radius from the center and the MOE and the MOR, respectively.

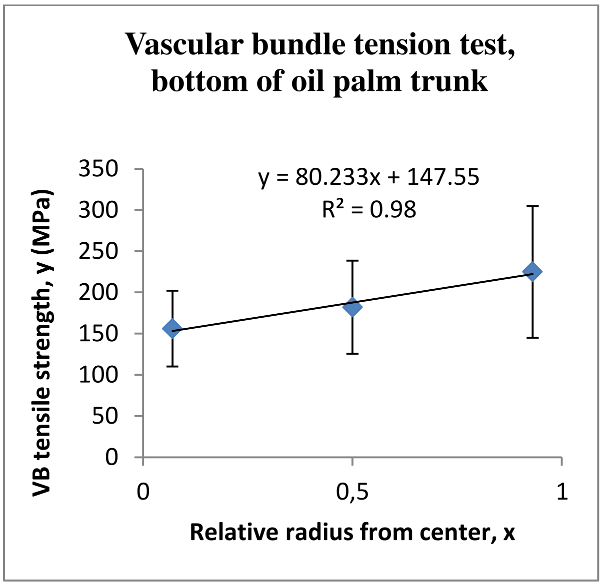
Table 23. Oil palm: Mechanical properties of vascular bundles *

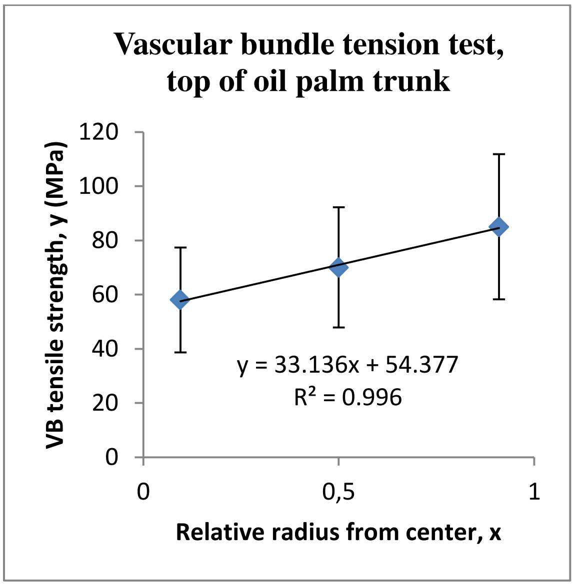
Stem height (m)	**Average* tensile strength (MPa)**			**Standard deviation**			**Average* elastic modulus (MPa)**			**Standard deviation**		
	P	C	I	P	C	I	P	C	I	P	C	I
7	85	70	58	26.8	22.2	19.4	5277	3341	2385	1001	1429	677
2	225	182	156	79.9	56.4	45.8	16973	13589	11135	5057	4308	3255

*Values shown for zones are based on 12 VBs; P "the bark" of the trunk (peripheral), C between outer and inner zones (central) and I near the core of the trunk (inner).

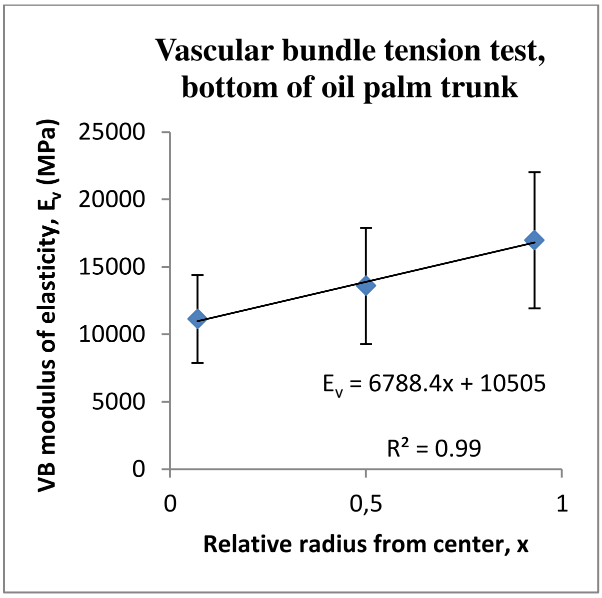
From Table 23 it becomes clear that the tension properties of single VBs at 7 m height are low in comparison to those of 2 m height. This can be explained by the (young) age of the VBs at the top of the tree which are composed of young cells only. According to Darwis et al. (2013), the top of the oil palm tree may have a higher proportion of VBs compared to the bottom. However, because the VBs are composed of young cells, the density and mechanical properties of the oil palm trunk at the top may be lower than at the bottom. Young cells have less secondary layers at the cell walls.

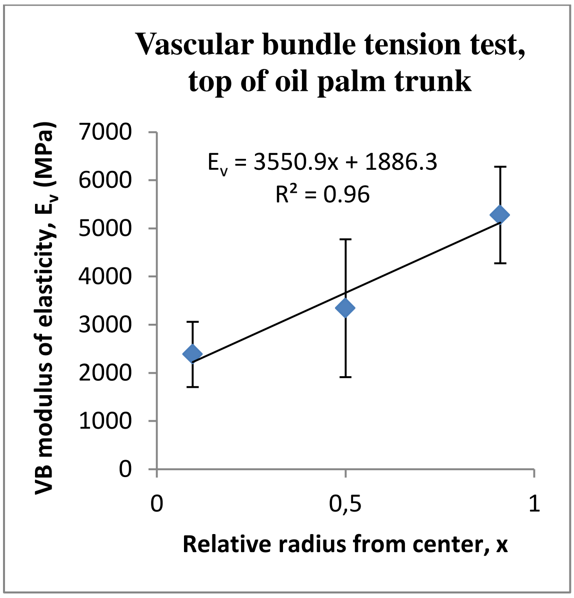
The effect is much bigger along height compared to radius. But the density and the strength of the wood are not affected so much as it could be concluded from VB strength. This phenomenon will be discussed in chapter 5.4.





(a_1) (a_2)





(b_1) (b_2)

Figure 43. Oil palm: Variation in the mechanical properties of vascular bundles along the radial direction: (a_1 and a_2) tensile strength and (b_1 and b_2) modulus of elasticity

These data demonstrate clearly that the relationships are described very well by simple linear models. The VBs near "the bark" of the trunk show higher values than those near the trunk core (Figure 43a_1, a_2) and the strength variation for all three zones can be expressed by the following formulas:

bottom of oil palm trunk: $y = Ax + B$

top of oil palm trunk: $y = A_1x + B_1$

where y is the tensile strength of VB and x is the relative radius from the center. Thus, x= 0 corresponds to the trunk radius= 0 and x= 1 to the outer surface of the trunk.

The VB near the bark of the trunk are stiffer (higher MOE) than those near the trunk core (Figure 43b_1, b_2). The MOE increases linearly with the relative radius from the center to the "bark" in a similar way as the MOR. The regression can be described with E_v as the MOE of the VB:

bottom of oil palm trunk: $E_v = ax+b$

top of oil palm trunk: $E_v = a_1x+b_1$

Table 23 shows the tensile strength and the MOE for the VB of two tree heights and three zones. When calculating the MOR×share of VB and compare the result with the tension strength of oil palm wood (Erwinsyah 2008) a close correlation between the VB-strength and the wood strength is obvious (Table 24 and Figure 44). This means that the tension strength of oil palm wood is dominated by the strength and the share (volume fraction, number and diameter) of the VB.

Table 24. Oil palm: MOR-analysis (comparison (VB MOR×share of VB) and wood MOR)

Trunk height (m)	Zones	MOR VB (N/mm^2)	Share of VB	MOR VB×share of VB	MOR wood (N/mm^2)[1)]
7	P	85	0.31	26	26
	C	70	0.27	19	15
	I	58	0.16	9	7
2	P	225	0.26	58.5	57
	C	182	0.16	29	38
	I	156	0.13	20	23

1) According to Erwinsyah (2008)

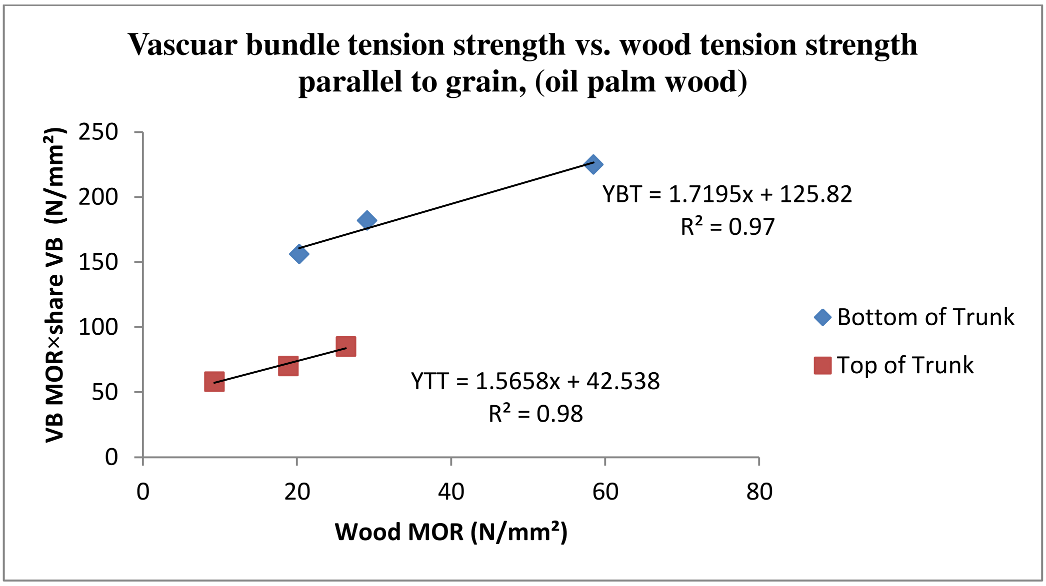


Figure 44. Relationship between tension strength of VBs (MOR VB×share VB) and tension strength of wood

5.1.3 Vascular bundles from date palm wood

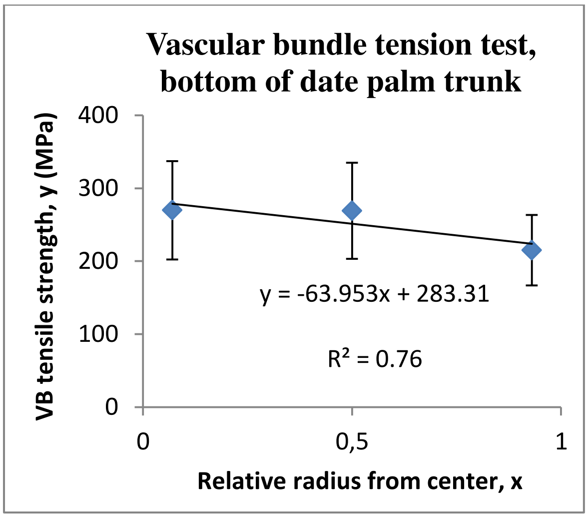
To investigate the variation in the mechanical properties of VBs in the radial direction of date palm trunk, more than 12 VBs in subsections (1, 3, 4, 6 from top of tree and 1, 5, 9 from bottom of trunk; Figure 25) were separated and tested. The average strength and average Young's modulus of VBs from each zone were measured. The test results for tension properties of single VBs (the MOE and the MOR) are given in Table 25. Figure 45 shows the relationship between the MOE and the MOR, respectively and the relative radius from center.

Table 25. Date palm: Mechanical properties of vascular bundles*

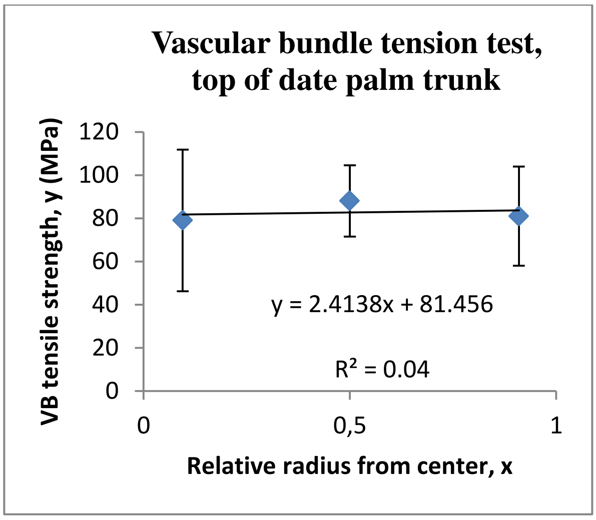
Stem height (m)	Average tensile strength (MPa)			Standard deviation			Average elastic modulus (MPa)			Standard deviation		
	P	C	I	P	C	I	P	C	I	P	C	I
7	81	88	79	22.9	16.5	32.8	2218	3577	3540	340	400	473
2	215	269	270	48.3	65.9	67.4	14273	17699	18466	2575	3553	4174

*Values shown for zones are based on 12 VBs; P near "the bark" of the trunk (peripheral), C between outer and inner zones (central) and I near the core of the trunk (inner).

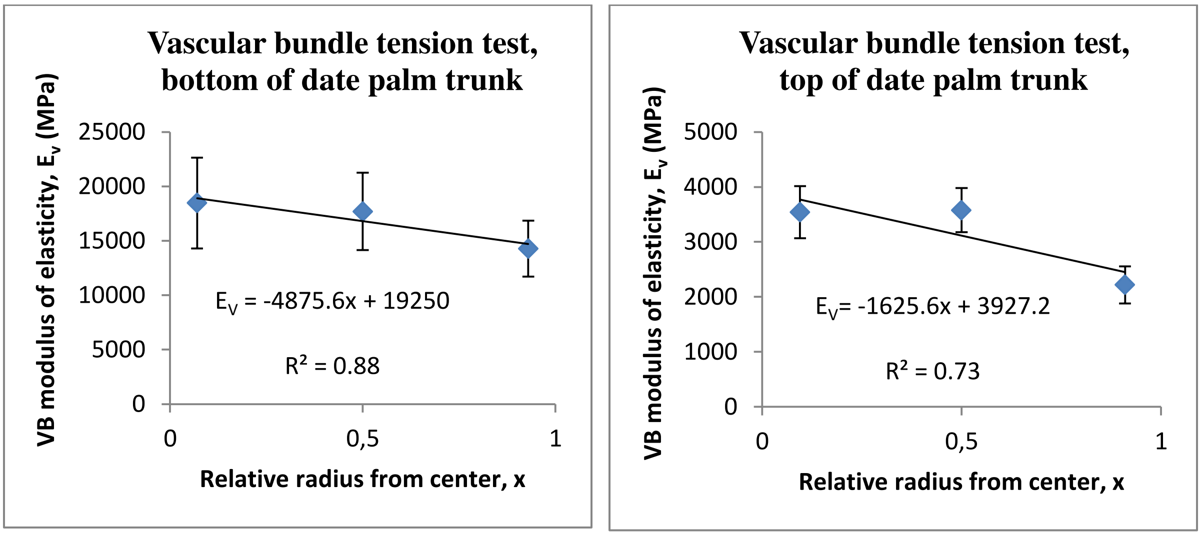
From Table 25, it becomes clear that single VBs of date palm wood in the inner zones have higher tension properties (MOE/MOR) compared to those in the outer zones. No explanation could be found for these differences, which are contrary to coconut and oil palm. No indication is given in the literature. This observation should be clarified in further research. Contrary to the variation in the properties of in the radial direction of the trunk, the tension properties of single VBs at 7 m height are only 20-25% of the 2 m height (like oil palms). This can be related as for oil palm to presence of the VBs which are composed by young cells in the top of tree (Darwis et al. 2013). As for oil palm the effect is much bigger along the height compared to the radius. However, the density and the strength of the wood are not different so much (discussion in chapter 5.4).



(a$_1$)



(a$_2$)



(b_1) (b_2)

Figure 45. Date palm: Variation in the mechanical properties of vascular bundles along the radial direction: (a_1 and a_2) tensile strength and (b_1 and b_2) modulus of elasticity

The relationship between the VB properties and the location follow a linear model. At the bottom of trunk, the VBs near "the bark" of the trunk show weaker properties than those near the trunk core (Figure 45a_1) but at the top of trunk, there is no significant difference between the inner and the outer zone of the trunk (Figure 45a_1). The strength variations for all three subsections can be expressed by the following formula:

bottom of date palm trunk: $y = Ax + B$

top of date palm trunk: $y = A_1x + B_1$

with y as the tensile strength of VB, and x as the relative radius from center.

The VBs near the trunk core are stiffer than those near the bark of the trunk (Figure 45b_1, b_2). The correlation between the MOE and the relative radius from center is linear similarly as with the tensile strength. It can be described by the following formula:

bottom of date palm trunk: $E_v = ax+b$

top of date palm trunk: $E_v = a_1x+b_1$

where E_v is the Young's modulus of VB.

Table 25 shows the tensile strength and the MOE for the VB of two tree heights and three zones. When the MOR×share of the VB is calculated and compared against the tension strength of date palm wood (Shamsi and Mazloumzadeh 2009), a close correlation between the VB-strength and the wood strength at the top of the trunk becomes obvious (Table 26 and Figure 46). Thus, the tension strength of date palm wood in the top of tree is dominated by the strength and the share (volume fraction, number and diameter) of the VB. However, the statistical evaluation revealed a weak correlation (R^2= 0.001) between the VB-strength and the wood strength at the bottom of tree. This observation suggests that other factors are important and influence the tensile strength properties (MOR-t) of the wood, especially the anatomical parameters such as (i) proportion of fibers in a vascular bundle, (ii) cell wall thickness, and (iii) microfibril angle in the cell wall layers. The fiber wall structure appears to be the single most important factor that determines the wood mechanical properties under the tensile and the bending stress among Calamus species (Bhat et al. 1990).

Table 26. Date palm: MOR- analysis (comparison (VB MOR×share of VB) and wood MOR)

Trunk height (m)	Zones	MOR VB (N/mm^2)	Share of VB	MOR VB×share of VB	MOR wood (N/mm^2)[1)]
7	P	81	0.33	27	n.a
	C	88	0.33	29	n.a
	I	79	0.27	21	n.a
2	P	215	0.33	71	66
	C	269	0.29	78	69
	I	270	0.24	65	60

[1)] According to Shamsi and Mazloumzadeh (2009)

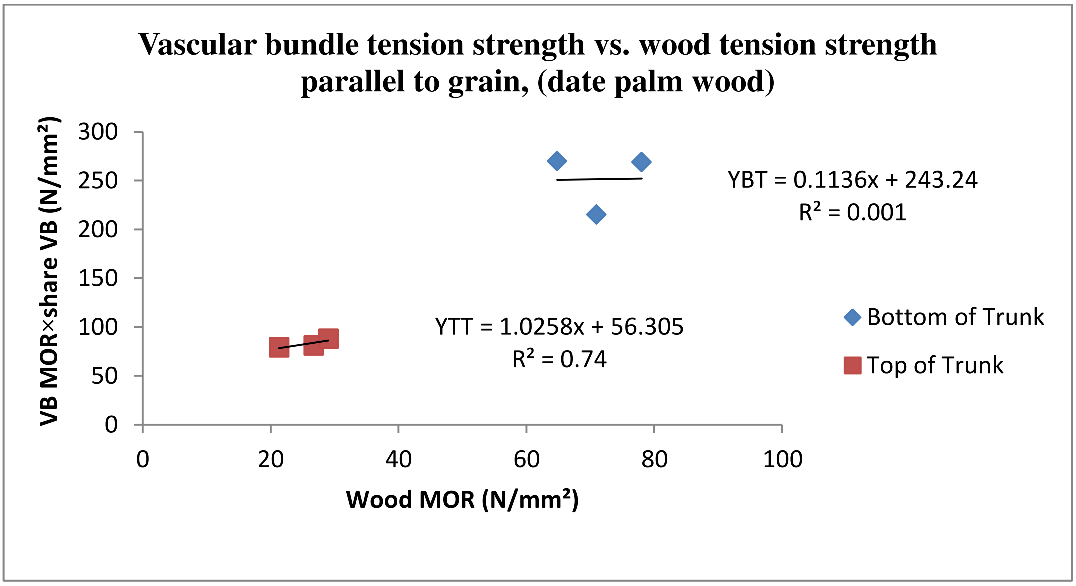
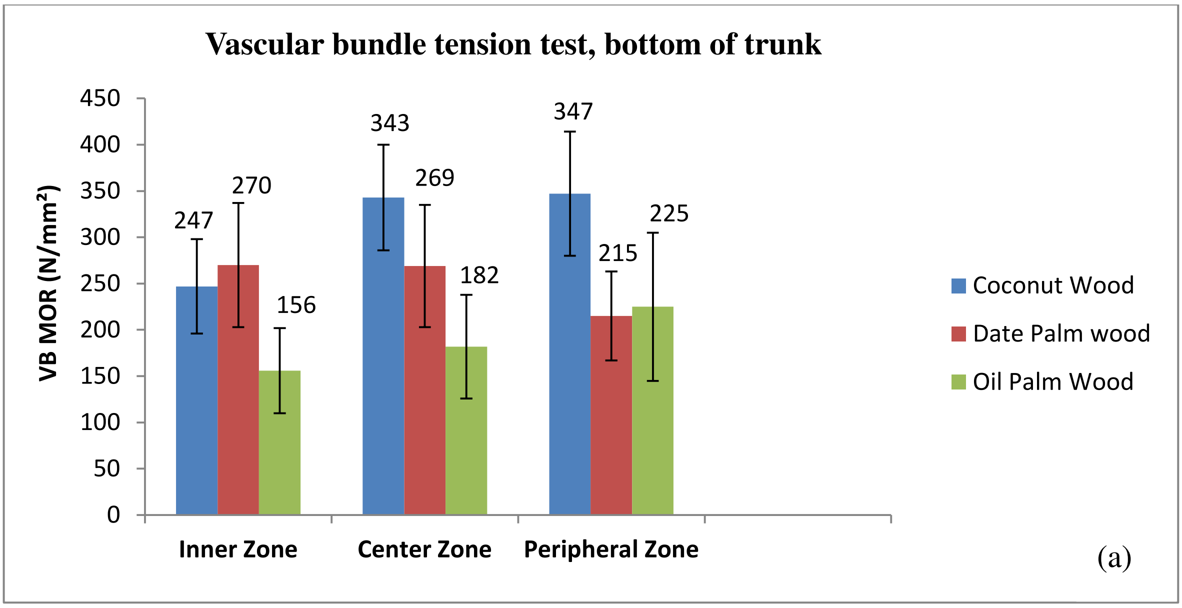


Figure 46. Relationship between the tensile strength of vascular bundles (MOR VB×share VB) and the tension strength of wood

5.1.4 Comparison between coconut, oil and date palm wood (only bottom of trunk)

Figure 47 shows the relationship between the VB tension properties (MOR/MOE) and the sample position along the trunk diameter in (coconut, oil and date palm) wood.



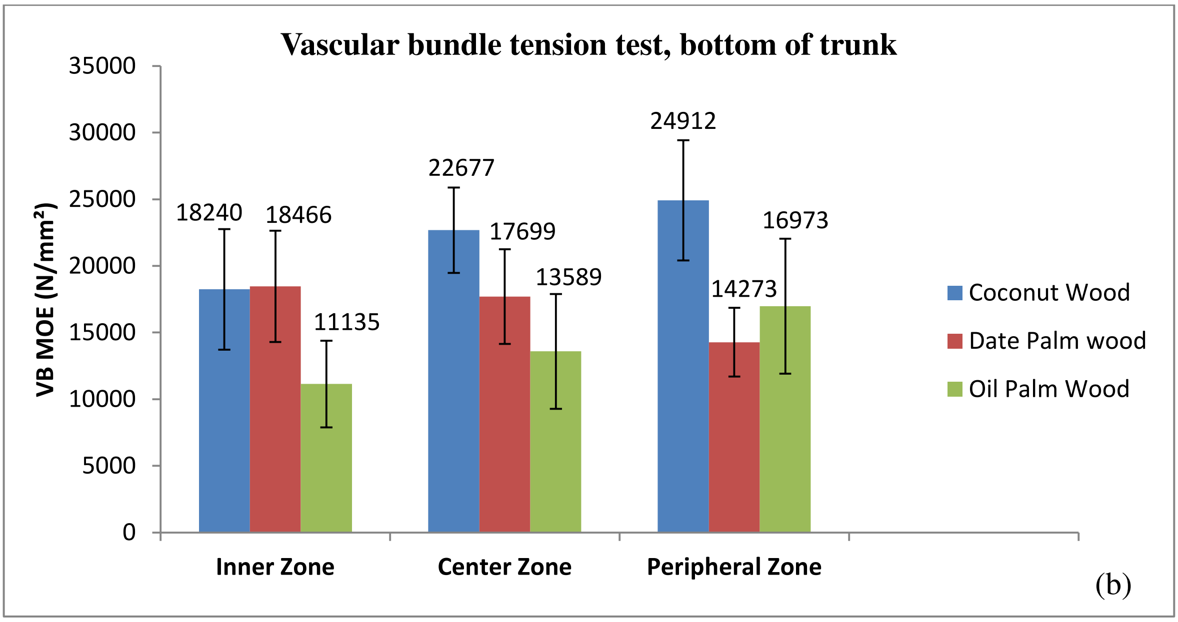


Figure 47. Relationship between the vascular bundle tension properties (MOR/MOE) and the sample position along the trunk diameter for coconut, date and oil palm wood: (a) modulus of rupture (b) modulus of elasticity

Figure 47 demonstrates clearly that the VBs tension properties (MOE) at given positions in coconut palm stem (bottom) are significantly higher than those in date and oil palm stems. This contrast is due to the generally higher of proportion of fibers in a vascular bundle and also higher number of cell wall layers in the fiber cell wall in coconut palms compared with date and oil palm wood (Killmann and Wong 1988).

More concrete also results in higher density of the wood in general. Presumably, the VB of coconut wood also has a higher density compared to oil and date palm resulting in stronger strength. Furthermore, the VB in coconut wood has more additional secondary layers, a higher concentration of cellulose and, therefore, higher tensile strength compared to the vascular bundle in date and oil palm wood. Because it is confirmed in general that the cellulose is mainly responsible for tensile strength in wood because of its special microfibrillar structure (e.g., Winandy and Rowell 1984).

5.2 Density characteristics

An important factor in determining the mechanical properties is the density of palm wood that increases from the core of the trunk toward the bark/peripheral zone. On the other hand, the density of palm wood is closely related to the distribution of VBs (Khozirah et al. 1991; Frühwald et al. 1992; Erwinsyah 2008).

5.2.1 Coconut wood from Mexico (bottom of trunk)

The average density divided into four subsections along the radius is shown in Table 27. The density shows a range of 0.41-0.82 g/cm³ (mean values) with the highest mean value at the outer zone (0.82 g/cm³). This involves thicker fiber walls and an increasing concentration of VBs in the outer zone of the trunk.

Table 27. Coconut (Mexico): Density of wood according to distribution in radial direction

Samples in zone[a]	Average density (g/cm³) at mc = 12 %	Min value	Max value	Standard deviation (g/cm³)
A1	0.82	0.79	0.83	0.02
A2	0.71	0.68	0.78	0.04
A3	0.53	0.49	0.56	0.05
A4	0.41	0.37	0.44	0.04

[a]Values are averages of 6 samples; A_1 is near "the bark" of the trunk, A_2 and A_3 are between outer and inner zones and A_4 is near the core of the trunk (see Figure 26b)

5.2.2 Coconut wood from Indonesia

12 pieces of wood (approx. 1000 mm×80 mm×26 mm), which represent the full range of density (Table 28) within the trunks were selected randomly from about 800 pieces in total.

Table 28. Density of coconut wood lumber pieces used for testing

Board/number	Air-dry density (g/cm³)
1	1.11
2	0.96
3	0.92
4	0.79
5	0.78
6	0.69
7	0.65
8	0.61
9	0.59
10	0.57
11	0.50
12	0.48

Indonesian coconut wood shows a wide range of densities in crosswise section. Taking the inhomogeneity and the practical experience with coconut wood (Killmann 1983; Frühwald et al. 1992) into account, three groups of density are considered in this study:

HD: high density timber (high, over 800 kg/m^3)

MD: medium density timber (medium, 600-800 kg/m^3)

LD: low density timber (low, below 600 kg/m^3).

Compared to the coconut wood from Mexico (Table 27), the Indonesian coconut wood is of higher density as shown by the comparison of the data for Mexico (Guzman 1989) and Indonesia (Frühwald et al. 1992). This may be caused by palm age, palm varieties and/or soil and climate conditions. Notably, the zones A1-A4 in Table 27 are average values of zones about 1/4×radius thick whereas the 25 mm boards from Indonesia represent 1/8×radius only. Consequently, for example, board No.1 in Table 28 is closer to the periphery.

5.2.3 Oil palm wood (bottom, middle and top of trunk)

The distribution of the density in oil palm trunks is shown in Table 29. The density was observed to be in the range of 0.30–0.59 g/cm^3 (average values) with the highest mean value at the outer portion from bottom of trunk (0.59 g/cm^3). This involves thicker fiber walls and an increasing concentration of VBs 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).

Table 29. Oil palm: Density distribution within trunks*

Trunk height (m)	**Average density (g/cm^3) at mc = 12 %**					
	P	SD	C	SD	I	SD
7	0.51	0.07	0.45	0.03	0.46	0.02
5	0.57	0.07	0.38	0.06	0.30	0.04
2	0.59	0.04	0.41	0.06	0.31	0.07

*Values are averages of 77 samples; P is near "the bark" of the trunk (peripheral), C is between outer and inner zones (central) and I is near the core of the trunk (inner). SD: Standard deviation.

Generally, the oil palm wood density at the transverse section increased gradually from the inner zone to the peripheral zone and decreased slightly from the bottom to the top of the trunk. The differences in the densities across the trunk diameter are higher than along the trunk. The density decrease from the outer to the inner zone of the trunk is lower at the upper part of the trunk than at the bottom part.

5.2.4 Date palm wood (bottom, middle and top of trunk)

The average density of date palm tree is shown in Table 30. The density was observed to be in the range of 0.62–0.70 g/cm³ with the highest mean value at the middle zone from bottom of trunk and the inner zone from middle of trunk (0.70 g/cm³).

Table 30. Date palm: Density distribution within trunks*

Trunk height (m)	**Average density (g/cm³) at mc = 12 %**					
	P	SD	C	SD	I	SD
7	0.64	0.03	0.67	0.02	0.69	0.03
5	0.62	0.01	0.68	0.03	0.70	0.03
2	0.67	0.02	0.70	0.03	0.67	0.02

*Values are averages of 82 samples; P is near "the bark" of the trunk (peripheral), C is between outer and inner zones (central) and I is near the core of the trunk (inner). SD: standard deviation.

In general these results show that there is no significant difference from inner to the outer zone of the trunk and also from bottom to the top of the trunk. No literature was found to confirm these findings.

5.2.5 Comparison between coconut, oil and date palm wood (only bottom of trunk)

The wood density has a significant impact on the physical and mechanical properties. Density is related to the number of VBs in the appropriate zone and to the fiber wall thickness in the VB and the parenchyma cells. 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 wood density is influenced by thicker walls in the parenchyma as well as in the VB cells (Bakar et al. 2012). Figure 48 shows the relationship between the density and the sample position along the trunk diameter in (coconut, oil, and date palm) wood.

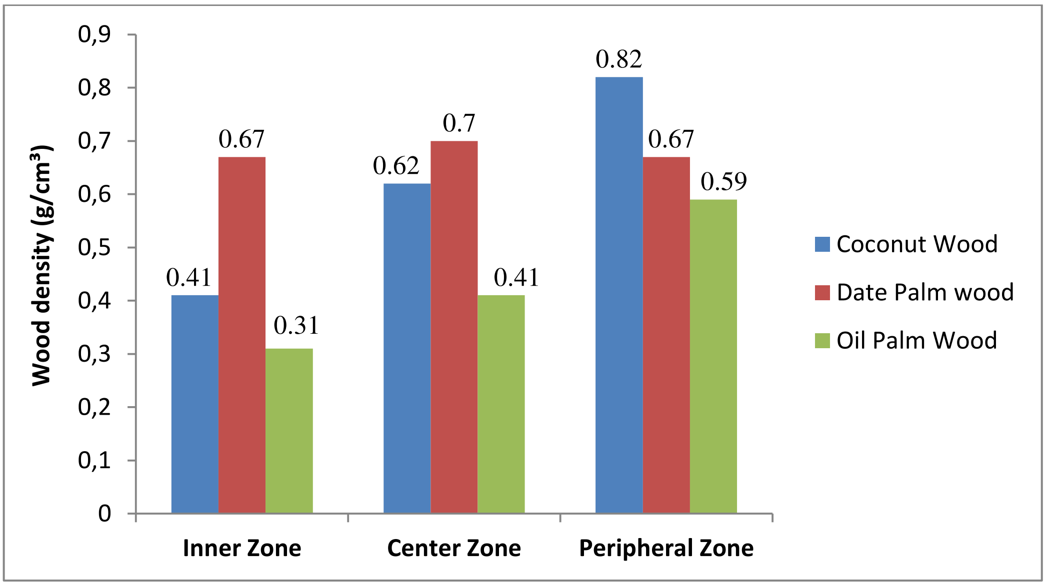


Figure 48. Relationship between the density and the sample position along the trunk diameter (coconut, date and oil palm) wood

The density of the wood varies along the stem height and across the diameter (Table 31). The density variation requires special sawing patterns and innovative grading procedures (air dry lumber) with the density as the main criterion, no knots (!) in order to produce lumber attributed to the density/strength classes (Frühwald et al. 1992). For coconut palm, three density classes are common: low density (LD) <0.50 g/cm³, medium density (MD) 0.50–0.70 g/cm³, high density (HD) > 0.70 g/cm³ (For oil palm, it is proposed to use LD <0.30/ MD <0.50 and HD > 0.50).

Table 31. Average density (oven dry) within the stem

Tree species	1	2	3	4
Coconut palm	0.82	0.41	0.61*	0.26*
Oil palm	0.59	0.31	0.51	0.46
Date palm	0.67	0.67	0.64	0.69
Scots pine**	0.48	0.45	0.46	0.42

*Guzman (1989)

**Kollmann (1951), own estimates for variation

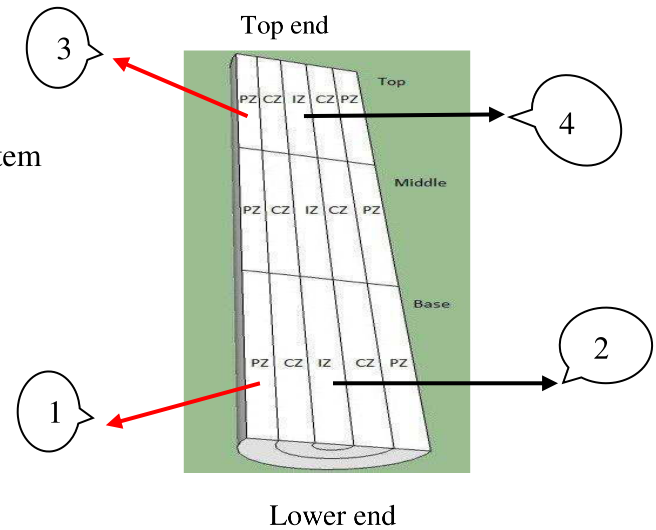


Figure 49. Three wood zones and three stem heights

For lumber uses it would be practical to grade/sort the palm stem material in outer, central and inner zones, to ensure an optimal utilization. But according to the results, for the date palm, this kind of sorting is not necessary because the densities along the cross section are similar.

5.2.6 Density of vascular bundles and parenchyma (coconut wood from Indonesia)

The average size and density of VBs, the parenchyma density and the density of wood are shown in Table 32. The density of VBs was observed to be in the range of 0.94-1.40 g/cm³.

Knowing the density of wood and VBs as well as the volume fraction of VBs, it is possible to calculate the density of parenchyma.

The summary of relationships between the mechanical properties and the overall density, the density of parenchyma and the density of vascular bundle in the Indonesian coconut wood have been discussed in the mechanical properties section (5.4).

Table 32. Coconut (Indonesia): Average size and density of vascular bundles, and parenchyma density

Board No.	**Average density of wood (g/cm³)**	**No. of VB taken**	**Area of VB, calculated from (a+b)* (cm²)**	**Average density of VB (g/cm³)**	**Average density of parenchyma (g/cm³)**
1	1.14 (0.01)	5	0.0079 (0.0013)	1.40 (0.10)	0.85 (0.08)
4	0.65 (0.02)	5	0.0079 (0.0008)	1.05 (0.12)	0.47 (0.04)
8	0.52 (0.04)	5	0.0075 (0.0009)	0.94 (0.16)	0.19 (0.06)

*a is diameter of VBs in tangential direction; b is diameter of VBs in radial direction of the trunk (See Figure 30 in chapter 4.2.2.1.2). Values in parentheses are standard deviation.

For determination of the VB density, weight and volume have to be measured. The shape of VB is very irregular (Figure 30a, b, c). Therefore, measuring different diameter and calculating cross area leads to different volumes and consequently, to different densities. In a test series a comparison was made to determine which diameters represent the cross area best (separate publication is under preparation). The best fit was achieved with the diameters a and b (Figure 30b, c). Therefore, the calculations in Table 32 were made using diameters a+b. However, it should be noted that the difference to the "true cross area" could still be high so that the VB-density and, therefore, the parenchyma density may vary and differ from the values in Table 32. Further research is necessary to determine volume fraction of VB (fiber caps and vessels).

5.3 Anatomical properties

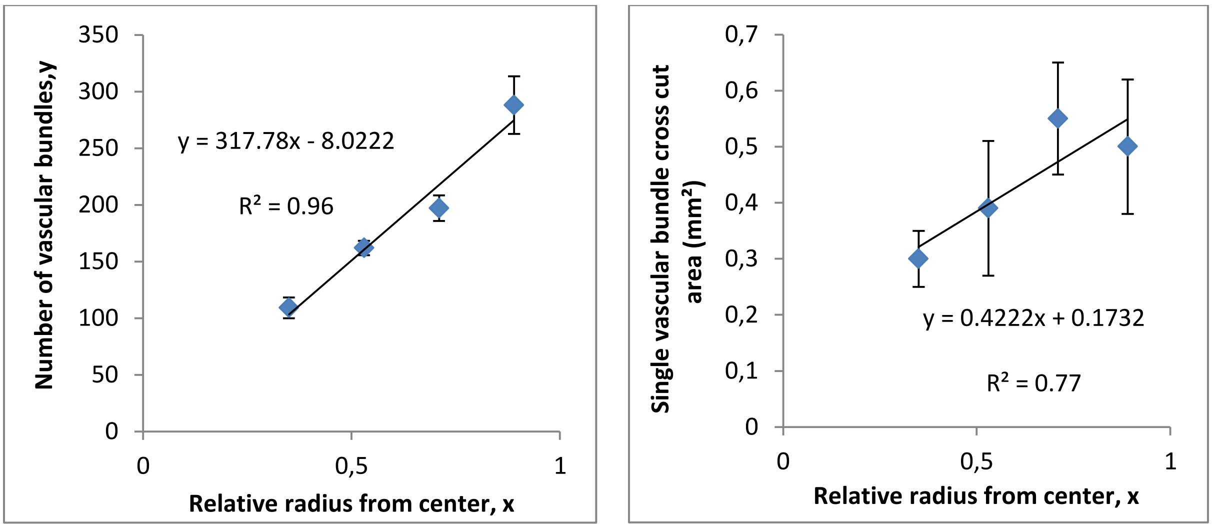
5.3.1 Coconut wood (bottom of trunk)

The anatomical properties of the coconut wood investigated are presented in Table 33 and Figure 50.

Table 33. Coconut palm: Number and dimension of vascular bundles

Samples in zones[a]	Number of VBs per 400 mm²	Single VB cross-cut area (mm²)[1)] (average)	Single VB diameter (µm)[2)] (average)	Total area of VBs (mm²) per 400 mm²	Share of VB (%)
A1	288 (25.5)	0.50 (0.12)[b]	878 (148)[b]	174 (27)	44
A2	197 (11.3)	0.55 (0.10)[b]	978 (125)[b]	148 (6.4)	37
A3	162 (6.4)	0.39 (0.12)[b]	855 (124)[b]	93 (1.4)	23
A4	109 (9.2)	0.30 (0.05)[b]	761 (94)[b]	50 (4.2)	13

[a]Values shown are averages of two samples with each 400 mm² square; [b]values shown are averages of 60 VBs; A_1 is near "the bark" of the trunk, A_2 and A_3 are in between outer and inner zones and A_4 is near the core of the trunk; values shown in parentheses are standard deviation. [1)] Measured with magic tool from Cell-F image software,. [2)] in tangential direction using Cell-F image software.



(a) (b)

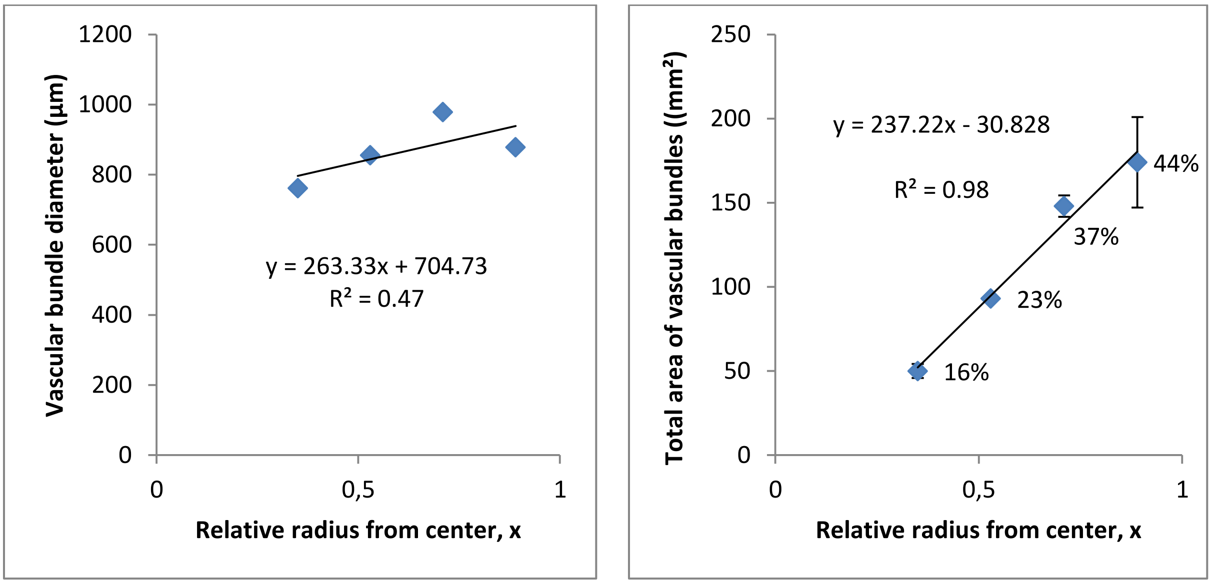


Figure 50. Coconut palm: Anatomical properties against the relative radius from center: (a) number of vascular bundles, (b) single VB cross-cut area, (c) VB diameter, (d) total area of VBs

The frequency of VBs varies significantly along the diameter of the trunk. The highest and the lowest mean area of VBs were observed in the outer zone (174.54 mm²) and the inner zone (49.59 mm²) (based on 400 mm² specimen area) which comprise 44% and 13% percentage of area/volume of the wood, respectively. The graphs in Figure 50 show the anatomical properties (number, single vascular bundle cross cut area, diameter and total area of VB) against the relative radius from center of the trunk. It is obvious that the relationship is well described by simple linear models. The anatomical properties near "the bark" of the trunk show higher properties than those near the trunk core. The vascular bundle diameter (measured in tangential direction) does not vary significantly along the trunk diameter (see Table 33).

5.3.2 Oil palm wood (bottom, middle and top of trunk)

The anatomical properties of the oil palm wood investigated are presented in Table 34 and Figure 51.

Table 34a. Oil palm: Number and dimension of vascular bundles

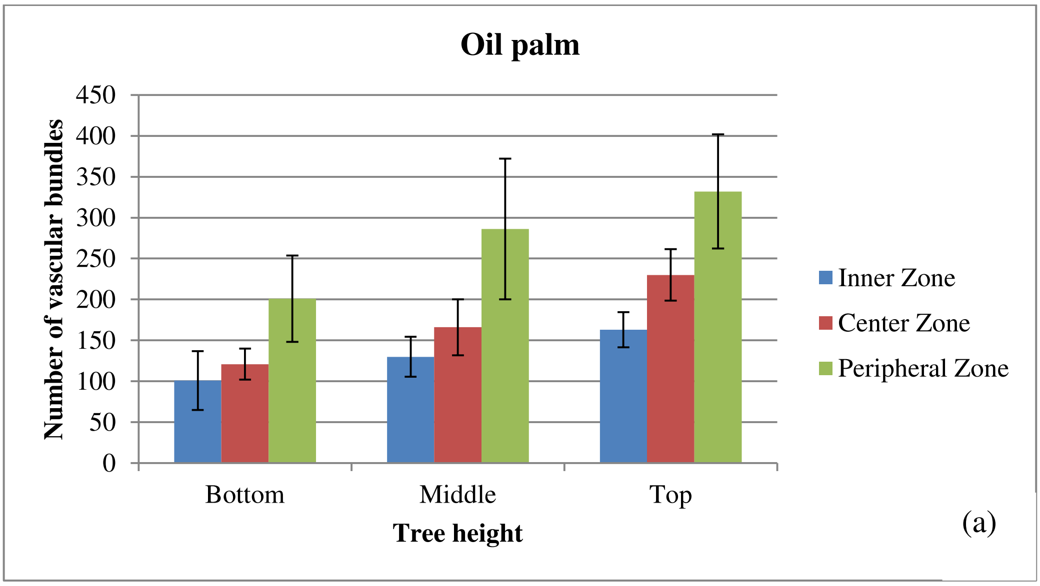
Stem height (m)[a]	Number of vascular bundles per 400 mm²			Single vascular bundle diameter (µm)[1)] (average)		
	P	C	I	P	C	I
7	332 (69.7)	230 (31.4)	163 (21.4)	692 (132.4)[b]	778 (166.7)[b]	713 (63.9)[b]
5	286 (86.0)	166 (34.3)	130 (24.4)	769 (72.8)[b]	808 (62.5)[b]	720 (32.8)[b]
2	201 (52.7)	121 (18.8)	101 (36.0)	817 (47.0)[b]	816 (45.2)[b]	816 (57.3)[b]
	Calculated total area of vascular bundles (mm²) per 400 mm²			**Measured single vascular bundle cross cut area (mm²)[2)] (average)**		
	P	C	I	P	C	I
7	125 (20.7)	109 (41.2)	65 (19.1)	0.22 (0.13)[b]	0.31 (0.25)[b]	0.24 (0.08)[b]
5	133 (14.4)	85 (11.1)	53 (13.6)	0.31 (0.09)[b]	0.34 (0.08)[b]	0.25 (0.03)[b]
2	105 (14.1)	63 (12.7)	53 (12.8)	0.35 (0.01)[b]	0.35 (0.02)[b]	0.35 (0.08)[b]

[a]Values are averages of 27 samples with each 400 mm² square; [b]values are averages of 270 VBs; values in parentheses are standard deviation; P is near "the bark" of the trunk (peripheral), C is in between outer and inner zones (central) and I is near the core of the trunk (inner). [1)] Cell-F image software was used for measuring in tangential direction. [2)] Measured with magic tool from Cell-F image software.

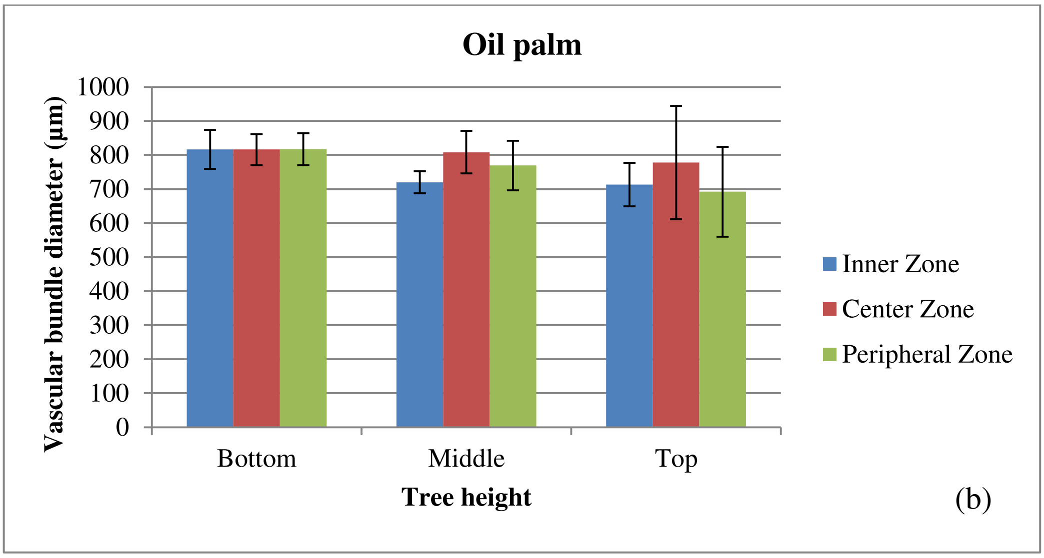
Table 34b. Oil palm: Share of vascular bundles on total cross section area

Stem height (m)[a]	% of VB on total area		
	P	C	I
7	31 %	27 %	16 %
5	33 %	21 %	13 %
2	26 %	16 %	13 %

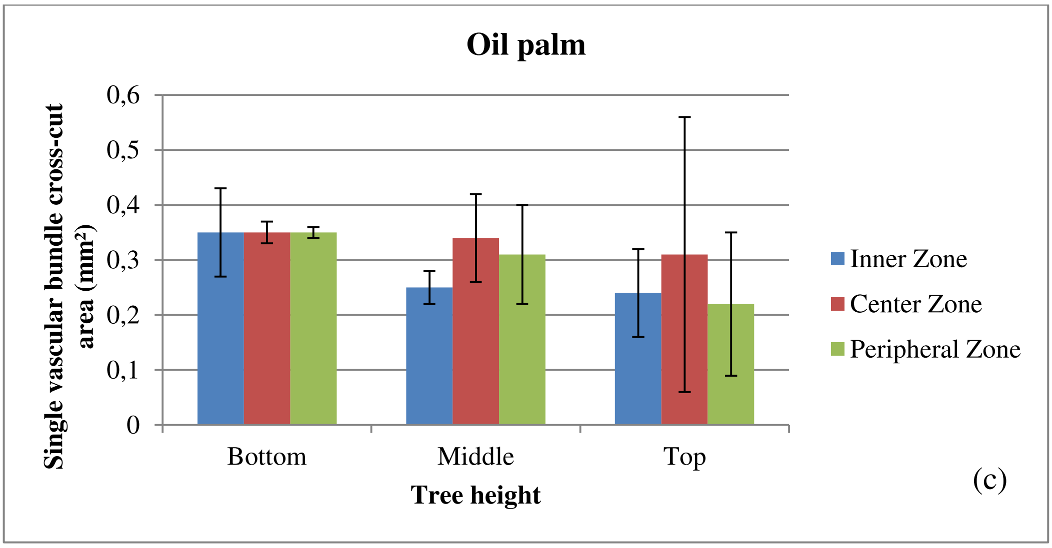
[a]Values are averages of 27 samples with each 400 mm² square; P is near "the bark" of the trunk (peripheral), C is between outer and inner zones (central) and I is near the core of the trunk (inner).



Oil palm
Number of vascular bundles
450
400
350
300
250
200
150
100
50
0
Bottom
Middle
Top
Tree height
Inner Zone
Center Zone
Peripheral Zone
(a)



Oil palm
Vascular bundle diameter (µm)
1000
900
800
700
600
500
400
300
200
100
0
Bottom
Middle
Top
Tree height
Inner Zone
Center Zone
Peripheral Zone
(b)



Oil palm
Single vascular bundle cross-cut area (mm²)
0,6
0,5
0,4
0,3
0,2
0,1
0
Bottom
Middle
Top
Tree height
Inner Zone
Center Zone
Peripheral Zone
(c)

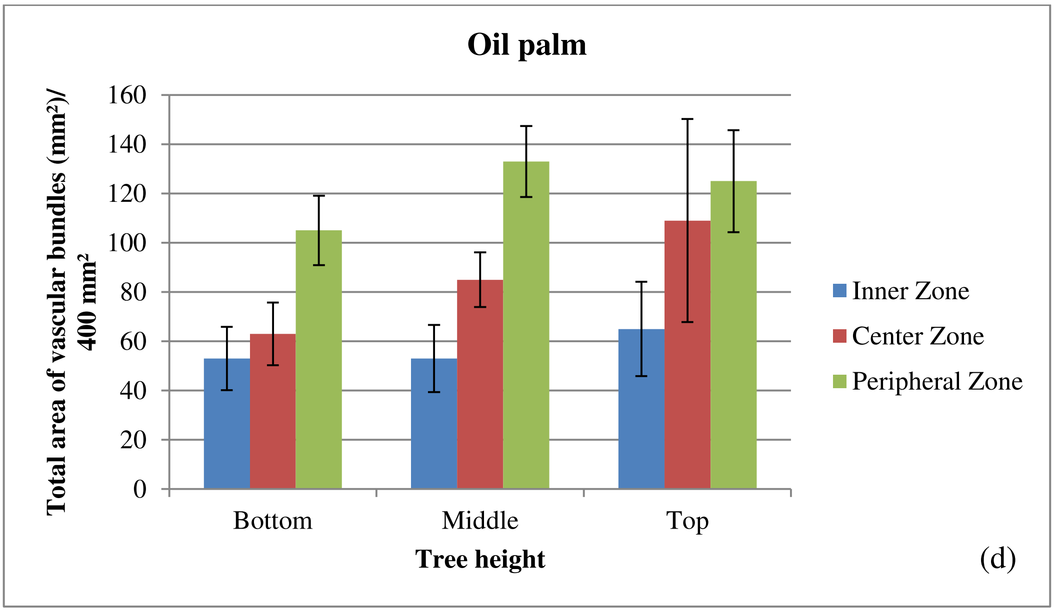


Figure 51. Oil palm: Anatomical properties against the oil palm tree height: (a) number of vascular bundles, (b) VB diameter, (c) single VB cross-cut area, (d) total area of VBs

The frequency of VBs varies significantly along the diameter of the trunk. It decreases from outside to inside (Table 34). Over the stem height, the frequency of VBs increases from the bottom to the top of tree (Table 34). The highest and the lowest mean area of VBs was observed in the outer zone from the intermediate height (133 mm^2) and the inner zone from bottom and middle of tree (53 mm^2), respectively (based on 400 mm^2 specimen area). The area, thus, comprise 33% and 13% percentage of area/volume of the wood. The graphs in Figure 51 show the anatomical properties against the tree height. The anatomical properties near ″the bark″ of the trunk show higher properties than those near the trunk core. However, over the tree height they show inconsistent values. The vascular bundle diameter (measured in tangential direction) does not vary significantly along the trunk diameter but over the stem height. The single VB diameter decreases from bottom to the top of tree. This finding is in agreement with Lim and Khoo (1986), who observed a decrease in width as well as in length of VBs over stem height of oil palm. The number of VB at the top of the trunk was significantly higher compared to the bottom. This is in agreement previous studies (Lim and Khoo 1986; Khozirah et al. 1991; Erwinsyah 2008; Darwis et al. 2013). A brief explanation was given in chapter 5.1.2.

5.3.3 Date palm wood (bottom, middle and top of trunk)

The anatomical properties of the date palm wood are reported in Table 35 and Figure 52.

Table 35a. Date palm: Number and dimension of vascular bundles

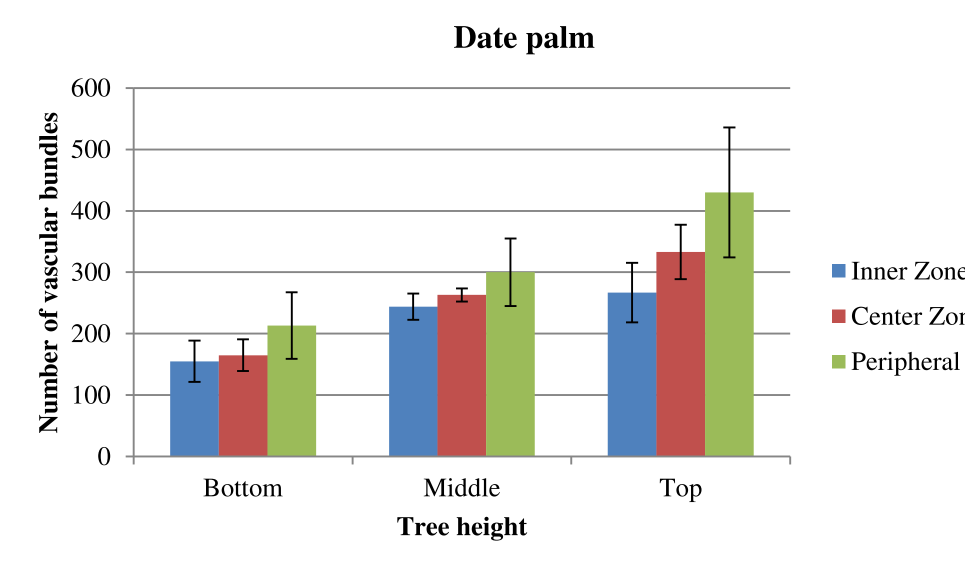
Stem height (m)[a]	Number of vascular bundles per 400 mm²			Single vascular bundle diameter (µm)[1)] (average)		
	P	C	I	P	C	I
7	430 (105.7)	333 (44.3)	267 (48.5)	622 (77.1)[b]	714 (13.4)[b]	719 (13.58)[b]
5	300 (54.8)	263 (10.9)	244 (21.3)	710 (79)[b]	795 (57.4)[b]	716 (21.8)[b]
2	213 (54.2)	165 (26.0)	155 (33.7)	885 (110)[b]	946 (62.2)[b]	878 (75.1)[b]
	Calculated total area of vascular bundles (mm²) per 400 mm²			**Measured single vascular bundle cross cut area (mm²)[2)] (average)**		
	P	C	I	P	C	I
7	131 (22.6)	133 (15.1)	108 (14.4)	0.15 (0.02)[b]	0.24 (0.01)[b]	0.24 (0.01)[b]
5	119 (19.0)	130 (15.7)	98 (14.3)	0.24 (0.11)[b]	0.33 (0.07)[b]	0.24 (0.01)[b]
2	131 (12.7)	116 (7.99)	94 (8.7)	0.61 (0.09)[b]	0.6 (0.03)[b]	0.51 (0.11)[b]

[a]Values are averages of 31 samples with each 400 mm² square; [b]values are averages of 300 VBs; P is near "the bark" of the trunk (peripheral), C is between outer and inner zones (central) and I is near the core of the trunk (inner); values shown in parentheses are standard deviation. [1)] Cell-F image software was used for measuring in tangential direction. [2)] Measured with magic tool from Cell-F image software.

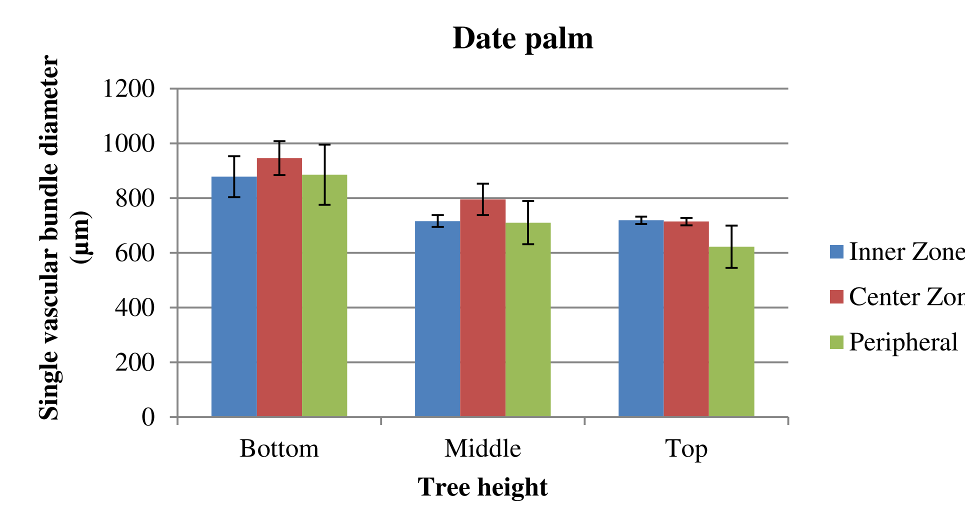
Table 35b. Date palm: Share of vascular bundles on total cross section area

Stem height (m)[a]	% of VB on total area		
	P	C	I
7	33 %	33 %	27 %
5	30 %	33 %	25 %
2	33 %	29 %	24 %

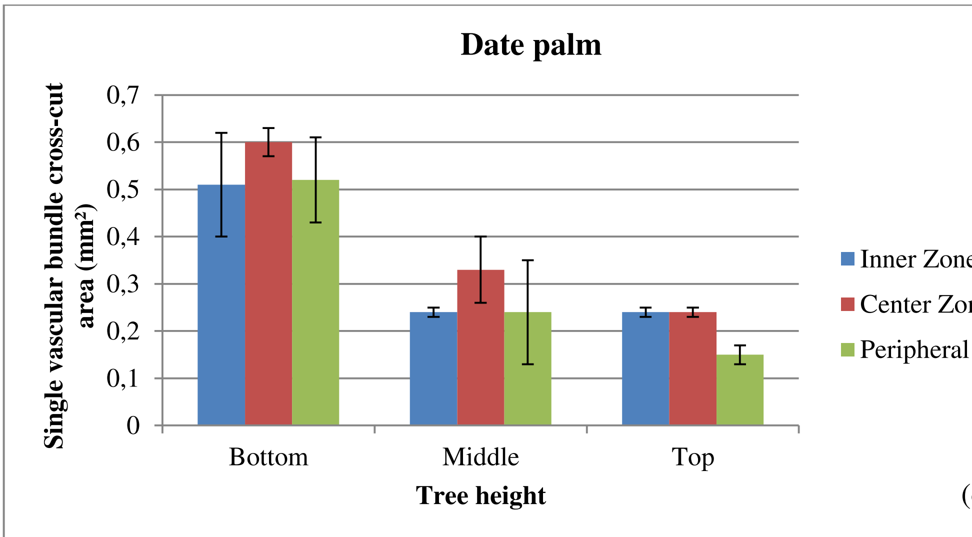
[a]Values are averages of 31 samples with each 400 mm² square; P is near "the bark" of the trunk (peripheral), C is between outer and inner zones (central) and I is near the core of the trunk (inner)


Date palm
Number of vascular bundles
600
500
400
300
200
100
0
Bottom
Middle
Top
Tree height
Inner Zone
Center Zone
Peripheral Zone

(a)


Date palm
Single vascular bundle diameter (µm)
1200
1000
800
600
400
200
0
Bottom
Middle
Top
Tree height
Inner Zone
Center Zone
Peripheral Zone

(b)


Date palm
Single vascular bundle cross-cut area (mm²)
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
Bottom
Middle
Top
Tree height
Inner Zone
Center Zone
Peripheral Zone

(c)

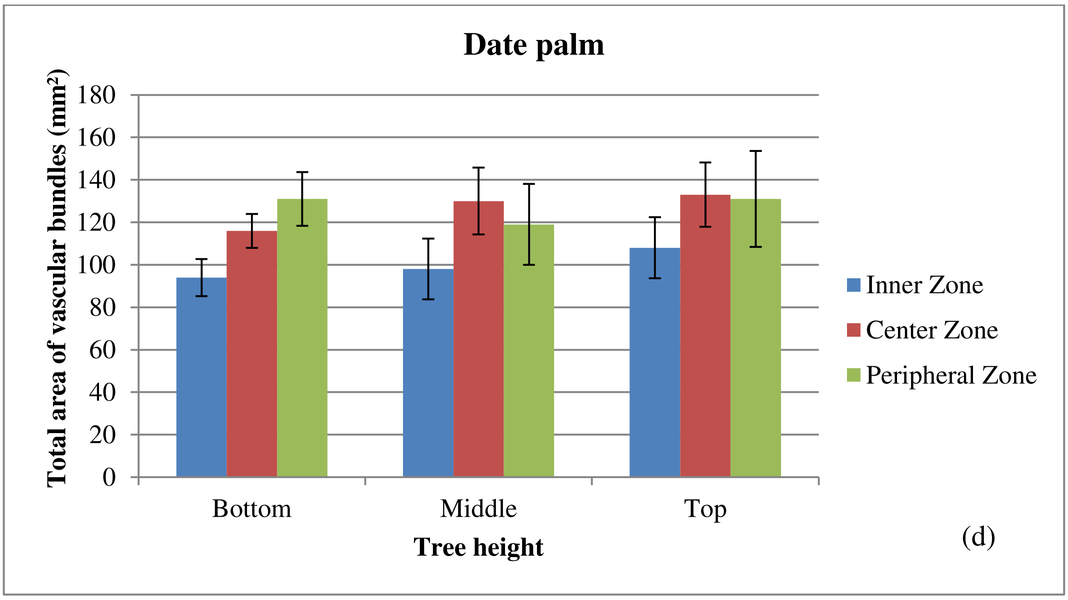
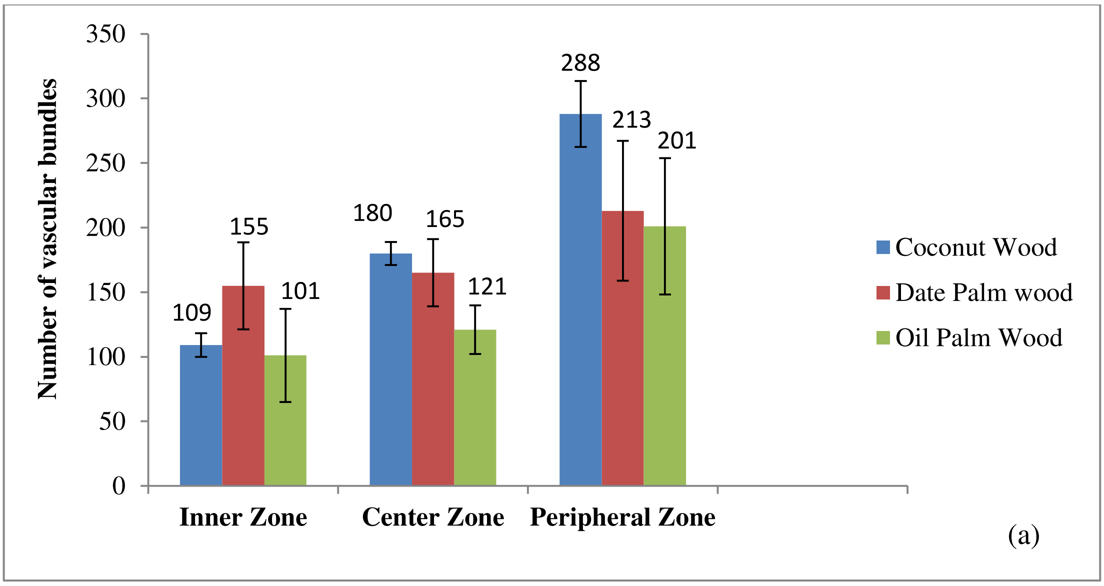


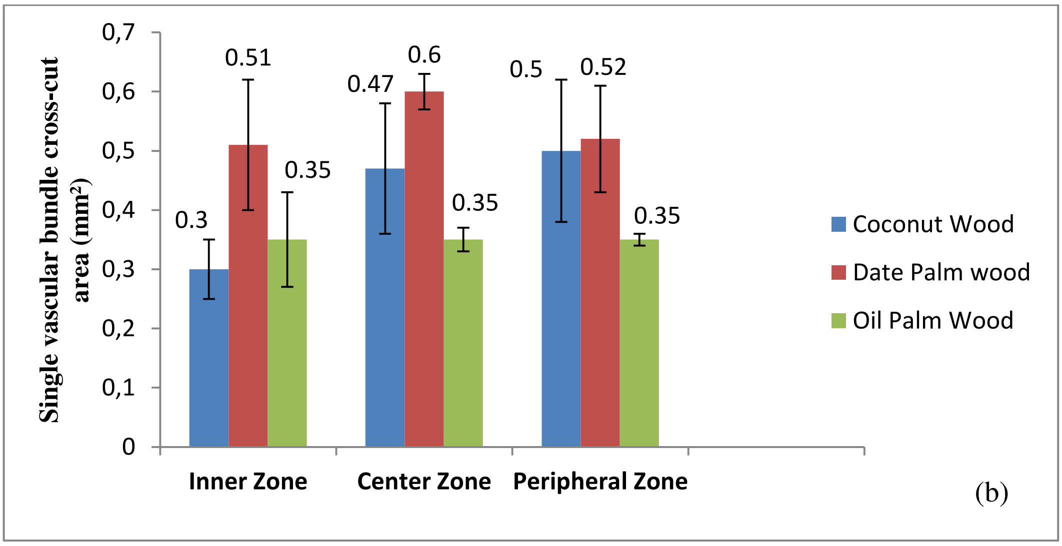
Figure 52. Date palm: Anatomical properties against the date palm trunk height: (a) number of vascular bundles, (b) single VB diameter, (c) single VB cross-cut area, (d) total area of VBs

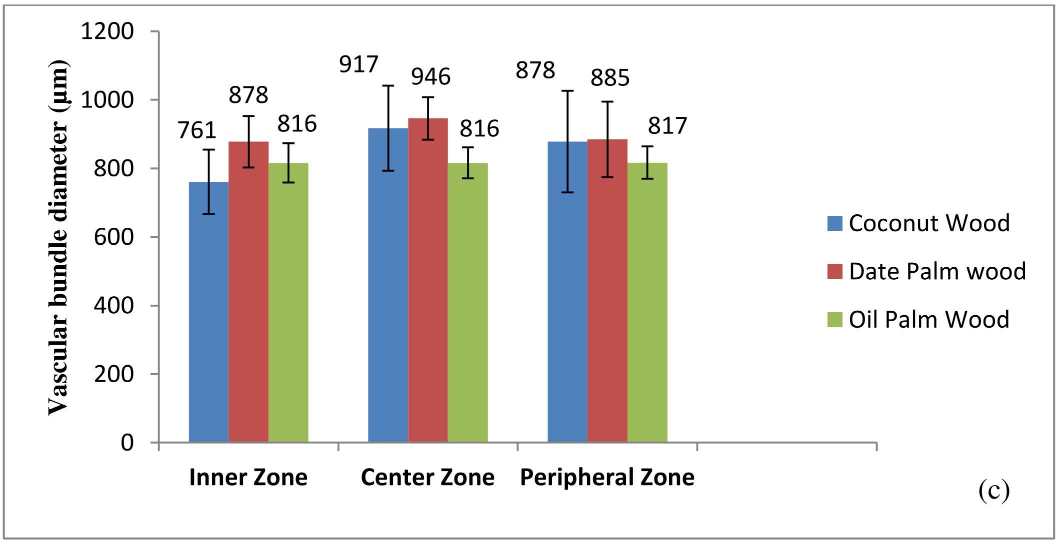
The frequency of VBs varies significantly along the diameter of the trunk. It decreases from outside to inside (Table 35). Over the stem height, the frequency of VBs increases from the bottom to the top of trunk (Table 35). The highest and the lowest mean area of VBs was observed in the middle zone from the top of trunk (133 mm^2) and the inner zone from bottom of trunk (94 mm^2, based on 400 mm^2 specimen area). The areas, thus, comprise 33% and 24% percentage of area/volume of the wood. The graphs in Figure 52 show the anatomical properties against the tree height. The anatomical properties near ″the bark″ of the trunk show higher properties than those near the trunk core but over the tree height they show inconsistent values. The vascular bundle diameter (measured in tangential direction) does not vary significantly along the trunk diameter but along the stem height while the VB diameter gradually decreases from bottom to the top of tree. The same trend was observed for the single vascular bundle cross-cut area of oil palm (Lim and Khoo 1986). No literature dealing with date palm was found to confirm these findings.

5.3.4 Comparison between coconut, oil and date palm wood (bottom of trunk)

All three palms investigated are monocotyledons. They do not have a cambium. Neither are they equipped with ray cells. A secondary thickening of the stem is the result of overall cell division and cell enlargement in the parenchymatous ground tissues, together with enlargement of the fibers of the VBs sheaths (Tomlinson 1961). It is 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 parenchyma and fiber caps and may explain the various densities, which are found; i.e. trunk base contains higher density of parenchyma compared to trunk top. Bakar et al. (2008) determined that the cell walls of the parenchyma tissues at the outer zones of the stem were thicker than those at the inner and the center. According to Gibson (2012), the concentration of VBs as well as the concentration of fibers within the VBs is greater at the outer zone of the trunk than in the inner zone. Darwis et al. (2013) reported that cells making up the VBs at the top of the palm wood are still of younger age than those at the lower trunk levels. Young cells have different properties than mature cells. These reasons make palm wood from the outer zones in comparison to inner zones and also at the bottom of trunk compared the top of the trunk to have a higher density. This is not valid for date palms in radial trunk direction (see chapter 5.2.4). Therefore, this aspect of aging of cell (aging of palm) is important for the density and (much more) for the properties. The stems of all three palms basically consist of a central cylinder surrounded by a narrow cortex. The central cylinder in all three palms consists mainly of ground parenchymatous tissues scattered with VBs. The VBs in the central part are large and few, but become smaller and closer together towards the periphery and underneath the cortex. The frequency distribution of VBs per 400 mm² in all three palms decreases from the outer zone to the inner zone (Figure 53a). The Figures 53a-d shows the relationship between anatomical properties and the sample position along the trunk diameter in (coconut, oil and date palm) wood.







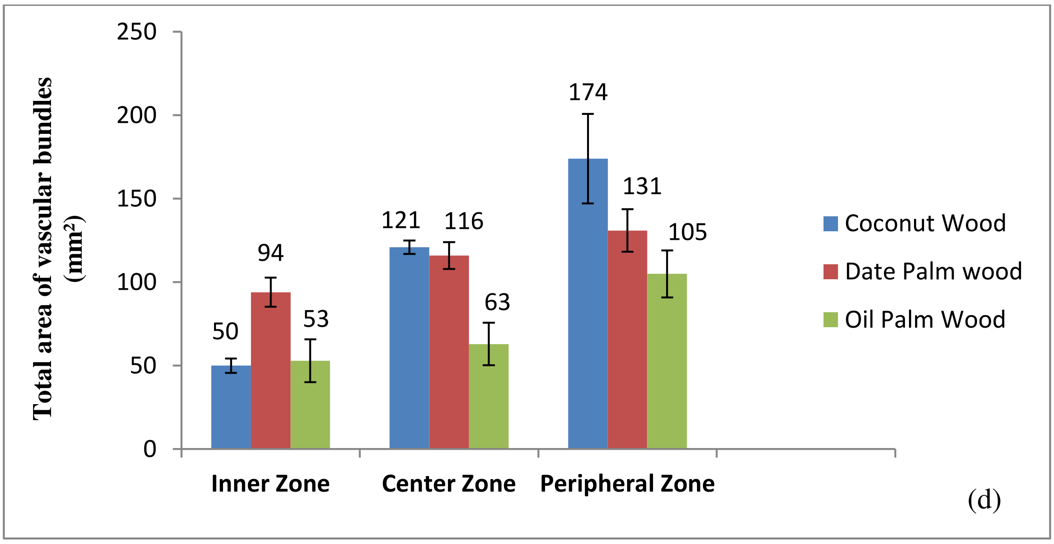


Figure 53. Anatomical properties against the sample position along trunk diameter (coconut, date, oil palm) wood: (a) number of vascular bundles, (b) single VB cross-cut area, (c) VB diameter, (d) total area of VBs

From Figure 53, it becomes clear that the anatomical properties (number of VBs and total area of VBs) at given positions in coconut palm stem measured from the outer zone of the bottom of tree is higher than those in date and oil palm tree. This is due to either genetic or physiological reasons. The increased number of VBs provides on one hand, better water transport (or guarantees transport if something happens to some VB) and on the other hand, gives more strength. One can argue that coconut palms are higher and need higher bending strength in the trunk (because of wind load and bending moment especially at the base of the trunk). From the viewpoint of fracture mechanics, it is clear that higher number of VB reduces stress and strain on a single VB, which results in lower shear stress at the interface between VB surface and the first neighboring parenchyma cells. Parenchyma cells have low shear properties because of their thin cell walls (although they become thicker with the "secondary diameter growth"). These results may explain why coconut trees have greater properties of survival against wind load in comparison to the date and oil palms, altogether they are taller.

The maximum number of VB is 288 per 400 mm² of the wood having a maximal total area of VB of about 40% on the cross section. Number and total area of VB has proven to be good indications for density and most mechanical properties (see chapter 5.3.1).

In coconut palm the single vascular bundle cross-cut area decreases from the peripheral to the inner zone of the trunk. But in date and oil palm there is no significant difference in diameter between the three different trunk diameter zones.

In all three palms (coconut, oil and date), the vascular bundle diameter (measured in the tangential direction) does not vary significantly along the trunk diameter (see Figure 53c). The VBs nearer the apex are younger and, therefore, smaller; those at any height level are of about the same maturity and would be expected to be almost similar in diameter (Lim and Khoo 1986). If VB diameter does not vary significantly along the trunk height, there is probably no secondary increase of the cell diameter (and finally trunk diameter) with age by adding additional layer at the top of the trunk. This would interfere with the assumption of secondary growth in the trunk diameter, which is at least not influenced by VB. The question whether parenchyma additional layer can cause this phenomenon was not the subject of this project.

However, in general, secondary growth means additional cell wall layers and consequently, increases in density, strength and trunk dimensions. Secondary growth has proven proofed to be an emerging aspect for further research.

The highest and the lowest mean area of VBs were observed in the outer zone of coconut wood (174.5 mm²) and the inner zone of coconut wood (49.6 mm² based on 400 mm² specimen area). They represent 44% and 13% percentage of area/volume of the wood, respectively. VB distribution, number and area of VBs are indicators for density and strength and they can be used for grading. In general, there is a high potential for density grading as the relationship between VB-parameters (and location in the trunk) is good. But for strength grading, the situation is much more complicated: Based on the structure of the wood (parenchyma tissue and VB as reinforcing structure elements) shear strength is lower compared to common timbers. Moreover, splitting behavior and nail holding is also lower. Screw holding is high because of anchorage of the screw between the VB. The VBs are very stiff (MOE). If the number of VB is high then the distance between two VB is small. If a screw is drilled into this wood, the screw is anchored at several VB. Even if the screw diameter is small, the screw will have a good holding capacity. But if there are less VB, then bigger diameter screws are needed. Also screw design can be optimized. An optimal strength grading technique has to set priorities, for which the strength properties are the most relevant.

The graphs in Figure 53 show that the anatomical properties in center and peripheral zones of coconut wood show higher values than those in oil 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.

5.4 Mechanical properties

The physical and mechanical properties such as density, swelling/shrinkage, MOE, MOR (tension, compression, bending), shear strength, nail and screw holding capacity, define the use of the timber for structural and non-structural purposes.

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). Tsoumis (1991) stated that wood exhibits different mechanical properties in different growth directions (axial, radial and tangential). Therefore, it is mechanically anisotropic. According to Bowyer et al. (2004), mechanical properties are usually the most important characteristics of 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. Structural uses of wood products include floor joint and rafters, structural panel roof, wall sheathing, sub flooring and etc.

5.4.1 Compression properties parallel to grain

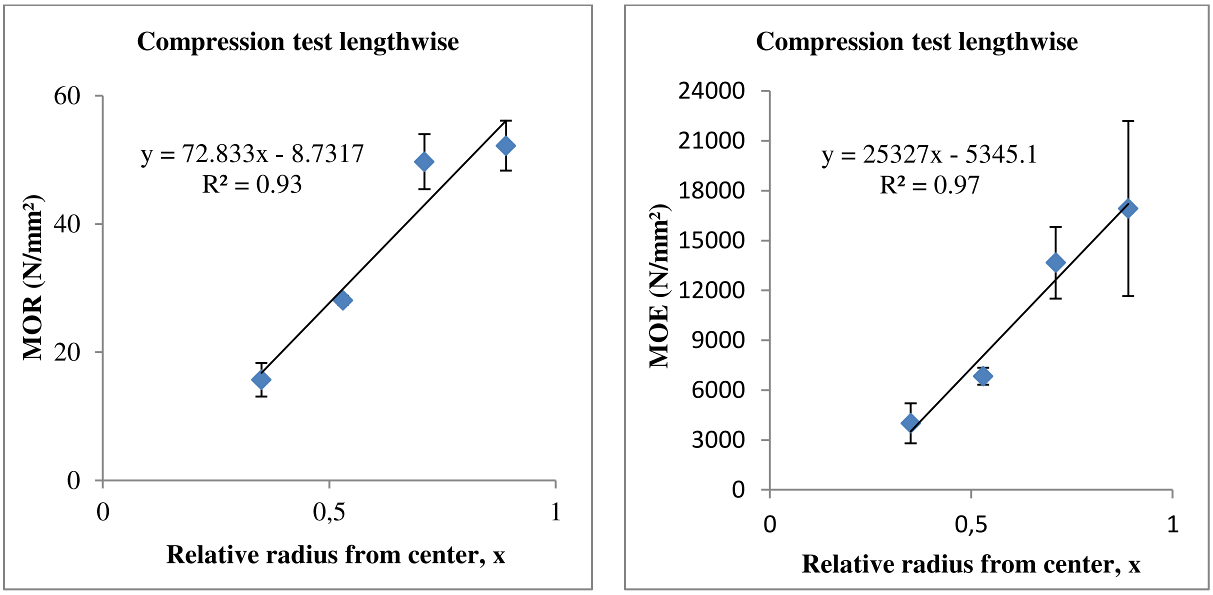
5.4.1.1 Coconut wood from Mexico (bottom of trunk)

For compression properties of coconut wood, test pieces (50 mm×20 mm) were cut from the outer to inner zone as shown in Figure 19b. Sixteen samples were used for the test. Table 36 and Figure 54 show the experimental results for compression test of coconut wood. The modulus of rupture (MOR) and modulus of elasticity (MOE) increase gradually from the inner zone to the outer zone in transverse direction.

Table 36. Coconut wood (Mexico): Average mechanical properties of coconut wood samples (compression test lengthwise)

Samples in zones[a]	**Density (g/cm^3)**	**SD (g/cm^3)**	**MOR (MPa)**	**SD (MPa)**	**MOE (MPa)**	**SD (MPa)**
A_1	0.80	0.02	52.2	3.9	16927	5261
A_2	0.74	0.04	49.7	4.3	13663	2154
A_3	0.49	0.02	28.1	0.7	6834	515
A_4	0.34	0.03	15.7	2.6	4007	1198

[a]Values for each zone are averages of 4 samples; A_1 is near "the bark" of the trunk, A_2 and A_3 are in between outer and inner zones and A_4 is near the core of the trunk.
SD: standard deviation.



(a) (b)

Figure 54. Coconut wood (Mexico): MOE and MOR for compression lengthwise

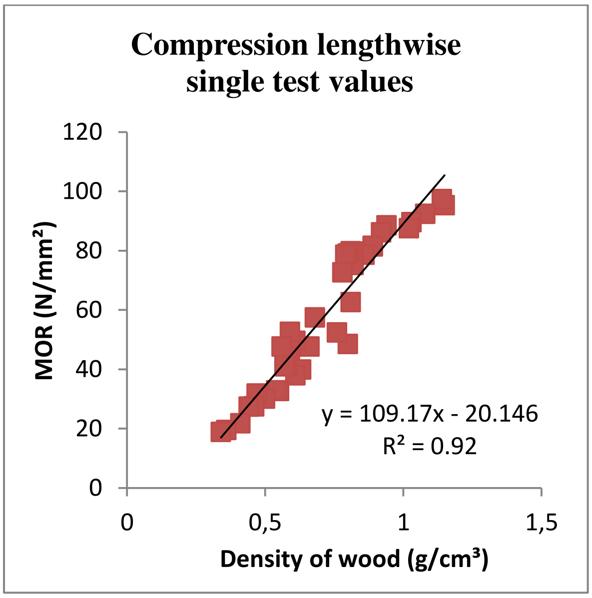
5.4.1.2 Coconut wood from Indonesia (bottom of trunk)

Test pieces were cut from the outer to inner zone and prepared as shown in Figure 33a. 40 samples were tested. The results are summarized in Table 37 and the relationship to density is given in Figure 55. The modulus of rupture (MOR) and modulus of elasticity (MOE) increase gradually from the inner zone to the outer zone along the radial direction.

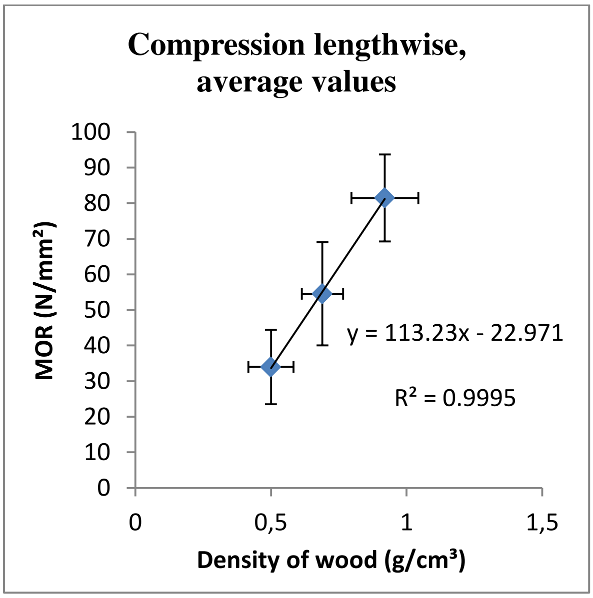
Table 37. Coconut wood (Indonesia): Compression test lengthwise, 12 % moisture content

No. of board	No. of specimen	Average density (g/cm³)	Average MOR (N/mm²)	Average MOE (N/mm²)
3 HD	16	0.92 (0.12)	81 (12.2)	19172 (4957)
6 MD	8	0.69 (0.08)	55 (14.6)	12782 (3687)
11 LD	16	0.5 (0.08)	34 (10.4)	7993 (2430)

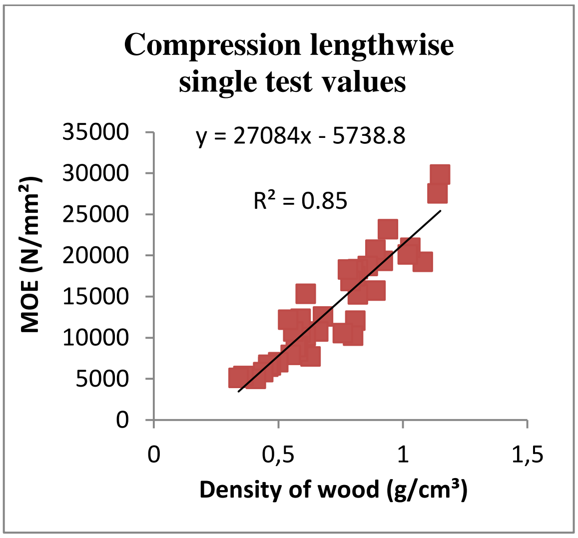
HD is near the outer zone, MD is in between outer and inner zones and LD is near the inner zone; values shown in parentheses are standard deviation.



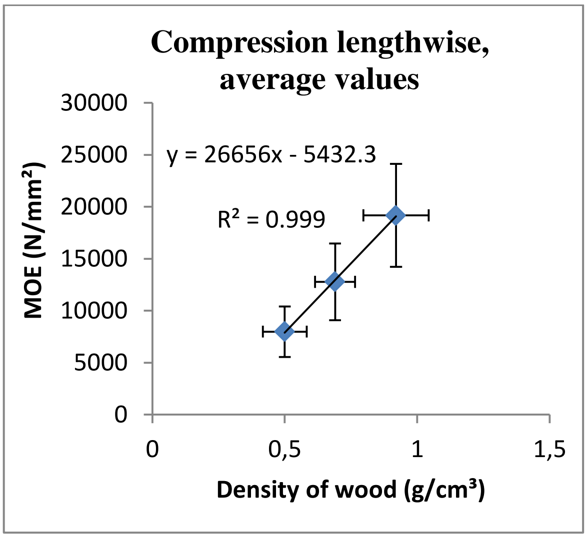
(a₁)



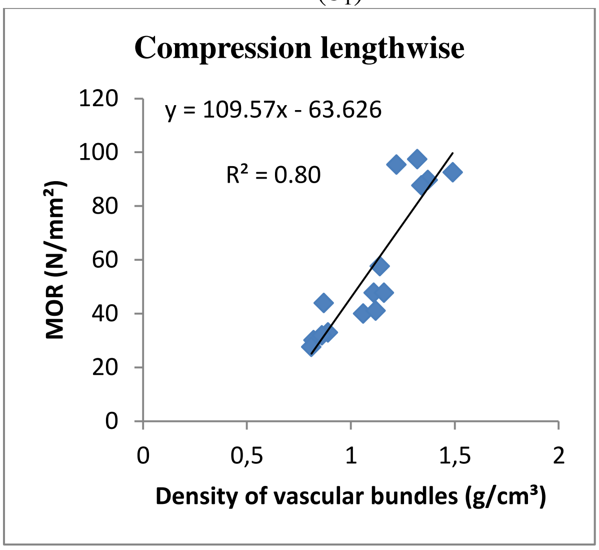
(a₂)



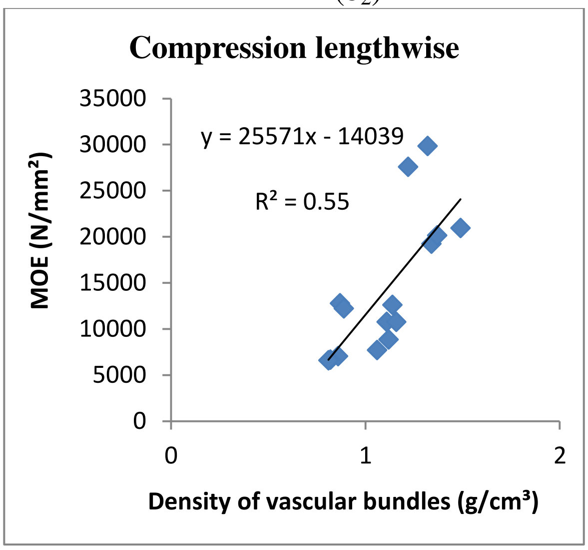
(b₁)



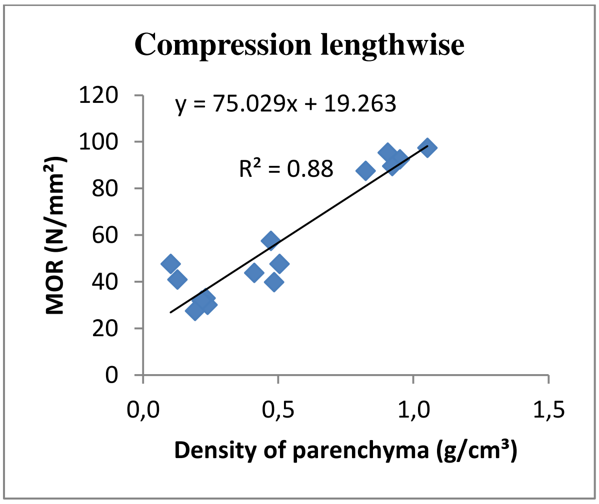
(b₂)



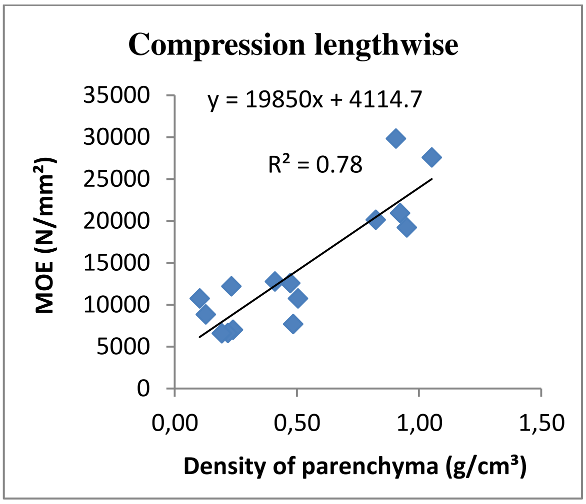
(c₁)



(c₂)



(d_1)



(d_2)

Figure 55. Coconut wood (Indonesia): MOR and MOE in compression lengthwise. MOR (a_1) and MOE (b_1) of all coconut samples along trunk diameter; MOR (a_2) and MOE (b_2) of three densities (boards); relationship between MOR (c_1) and MOE (c_2) and density of VBs; relationship between MOR (d_1) and MOE (d_2) and density of parenchyma

5.4.1.3 Oil palm wood (bottom, middle and top of trunk)

Regarding the mechanical properties of oil palm wood, only the compression parallel to grain properties were tested in this study. For tension test sufficient material was not available. It is intended to develop a mechanical model at a later stage showing the interrelation between the structural features and the mechanical properties. The testing was carried out on the basis of DIN 52185 standard for the compression properties.

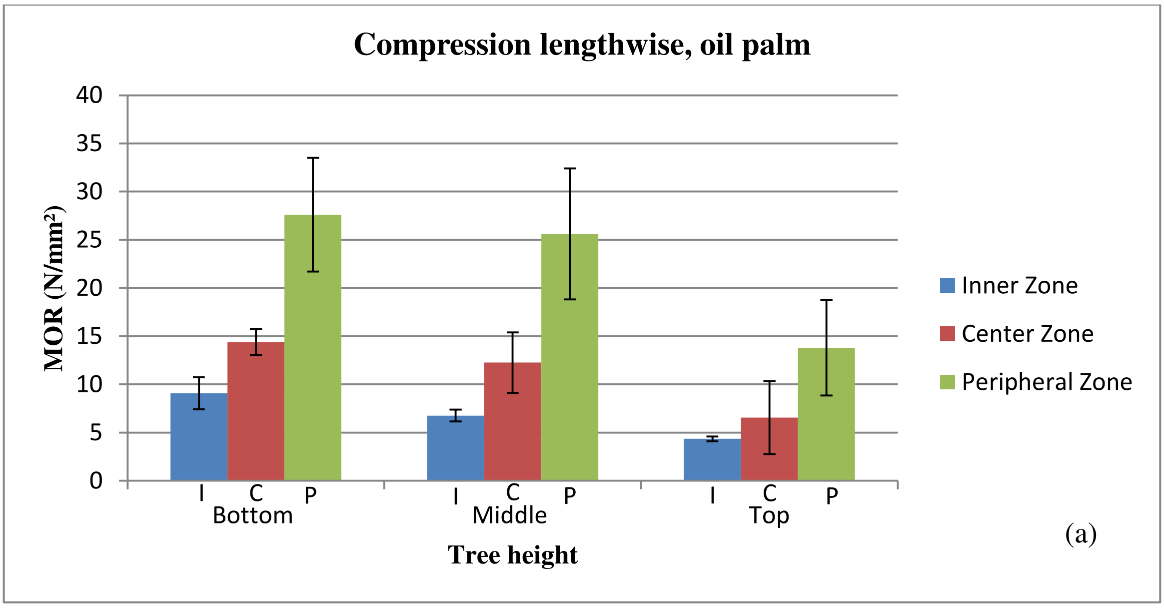
Dimension, condition, position and number of specimen and type of testing are presented in Table 20 (see section 4.1.2.3). Table 38 and Figure 56 show the experimental results for compression test of oil palm wood. The modulus of rupture (MOR) and the modulus of elasticity (MOE) are decrease drastically from the outer to the inner and from the bottom to the top.

Table 38. Oil palm wood: Compression test results (lengthwise)

Trunk height (m)[a]	Density (g/cm^3) (SD)			Compression test lengthwise MOR (MPa) (SD)			MOE (MPa) (SD)		
	P	C	I	P	C	I	P	C	I
7	0.54 (0.09)	0.46 (0.03)	0.47 (0.04)	13.8 (4.95)	6.55 (3.8)	4.35 (0.25)	7120 (1875)	2290 (800)	1856 (532)
5	0.56 (0.09)	0.38 (0.04)	0.31 (0.03)	25.6 (6.8)	12.26 (3.15)	6.77 (0.6)	8894 (2832)	5435 (785)	2327 (225)
2	0.59 (0.08)	0.42 (0.06)	0.31 (0.05)	27.6 5.9	14.41 (1.35)	9.08 (1.65)	8238 (1129)	4530 (78)	2997 (897)

[a]Values are averages of 27 samples from each zone; P is near "the bark" of the trunk (peripheral), C is in between outer and inner zones (central) and I is near the core of the trunk (inner). Values shown in parentheses are standard deviation.

Figure 56 shows the relation between the compression strength parallel to the grain of the oil palm wood and its trunk height.



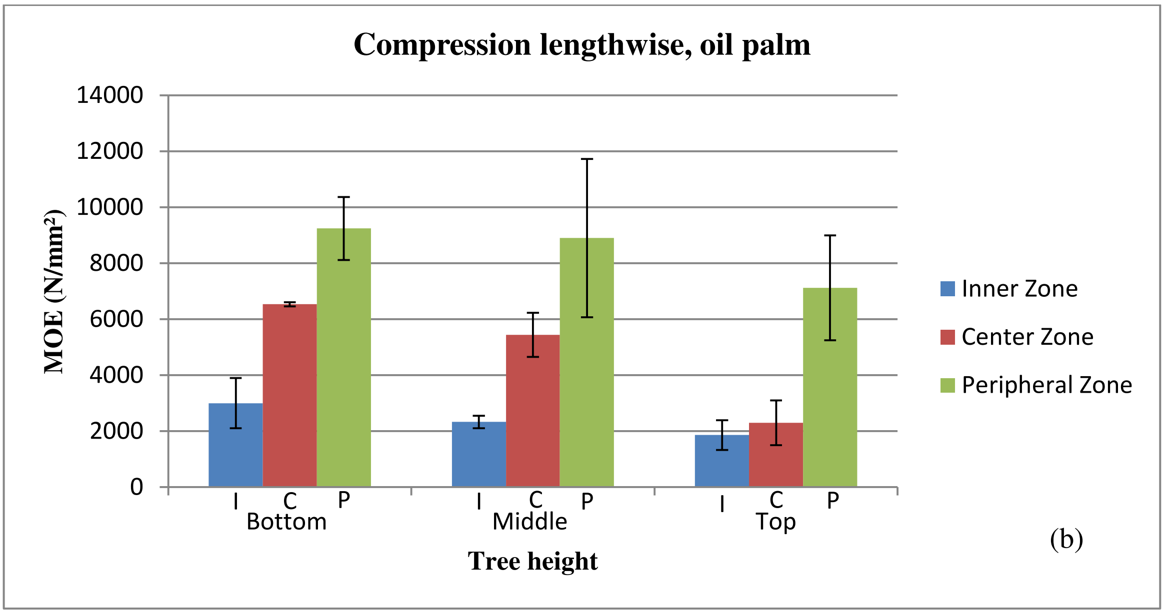


Figure 56. Oil palm wood: Compression MOR (a) and MOE (b) parallel to grain of oil palm wood at three different zones (inner, center, and peripheral zone) and three trunk heights

In order to investigate the effect of trunk height on the compression strength, the data in Table 38 showed that the average value for all samples is 13.38 N/mm² and single values ranging from 4.35 to 27.6 N/mm². It can be observed that the distribution of compression strength is 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. This result clearly shows that in the utilization of oil palm wood, the wood needs appropriate grading along the trunk height and the diameter.

5.4.1.4 Date palm wood (bottom, middle and top of trunk)

In this study, only the compression properties of date palm wood are considered. Sufficient material was not available to perform other tests. The tests were carried out according to DIN 52185. The dimension, condition, position and number of specimen and type of testing are presented in Table 21 (see section 4.1.3.3).

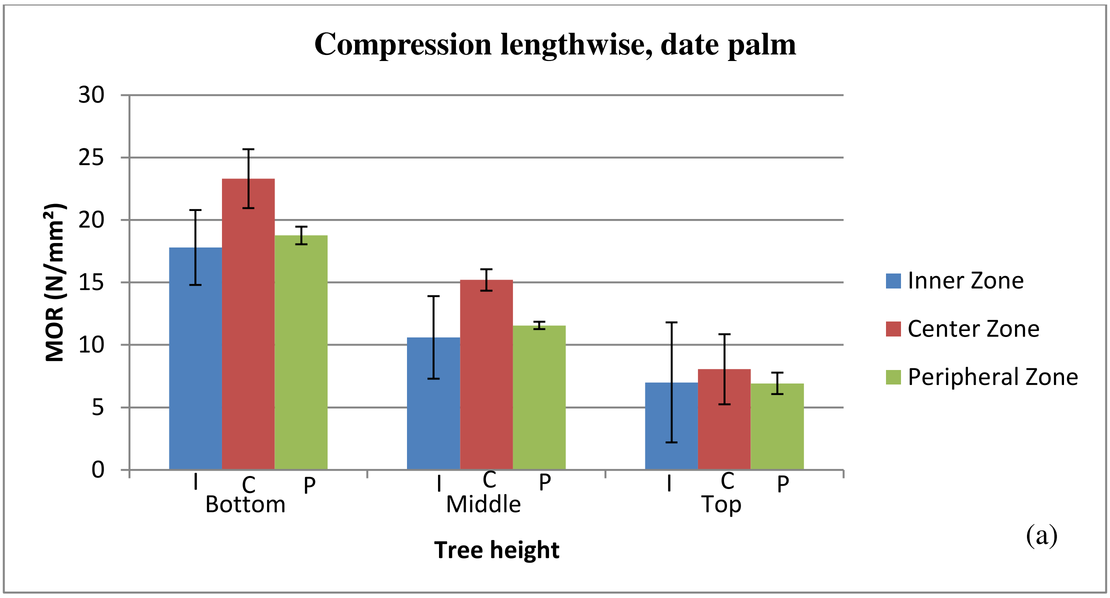
Similarly for oil palm, the results for MOR is spread very wide and ranges between 6.1 N/mm^2 (one sample, peripheral, top of trunk) to 21.31 N/mm^2 (one sample, center, bottom of trunk).

Table 39 and Figure 57 show the experimental results for compression test of date palm wood. The modulus of rupture (MOR) and the modulus of elasticity (MOE) fluctuate from the inner zone to the outer zone in the transverse direction but decrease drastically from the bottom to the top.

Table 39. Date palm wood: Compression test results (lengthwise)

Trunk height (m)[a]	Density (g/cm³) (SD)			Compression test lengthwise MOR (MPa) (SD)			MOE (MPa) (SD)		
	P	C	I	P	C	I	P	C	I
7	0.66 (0.02)	0.71 (0.01)	0.73 (0.02)	6.9 (0.85)	8 (0.3)	7 (0.7)	1257 (115)	1622 (171)	1376 (182)
5	0.66 (0.03)	0.70 (0.03)	0.72 (0.02)	11.6 (2.8)	15.2 (0.85)	10.6 (2.35)	3058 (1023)	3864 (144)	2925 (1408)
2	0.71 (0.05)	0.72 (0.03)	0.67 (0.03)	18.8 (4.8)	23.3 (3.3)	17.8 (3)	6396 (1593)	7003 (859)	6657 (2573)

[a]Values are averages of 31 samples from each zone; P is near "the bark" of the trunk (peripheral), C is in between outer and inner zones (central) and I is near the core of the trunk (inner). Values shown in parentheses are standard deviation.



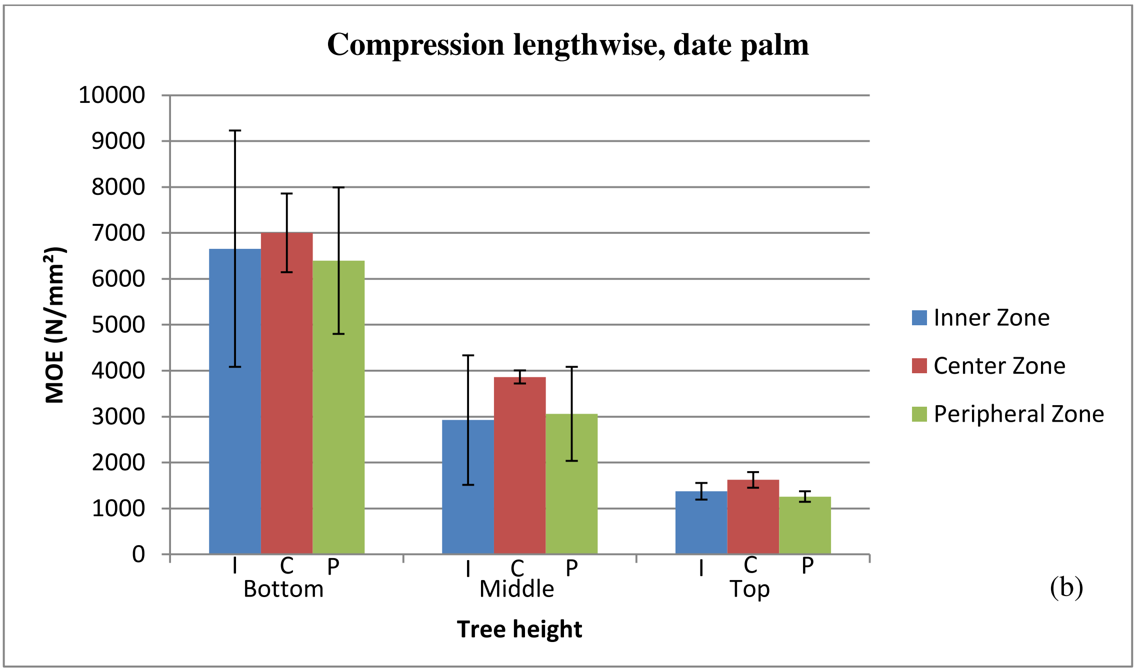


Figure 57. Date palm wood: Compression MOR (a) and MOE (b) parallel to grain at three different zones (inner, center, and peripheral zone) and three trunk heights

In order to investigate the effect of trunk height on the compression strength, the data in Table 39 showed that the distribution of compression strength is very much related to the position in the trunk. It decreases along the trunk height from the bottom to the top of the trunk, but the distribution of compression parallel strength along the trunk diameter was fluctuating from inner to the peripheral of the trunk (Figure 57a), but generally it was gradually decreased. These results clearly show that in the utilization of date palm wood, the wood needs good grading along the trunk height and diameter similarly as in other palms. In contrast to the other palms, the grading technique for date palm cannot be based on density mainly (if mechanical properties are targeted) because almost no correlation exists between density and mechanical properties.

5.4.1.5 Comparison between coconut, oil and date palm wood (bottom of trunk)

Mechanical properties reflect the density variation observed in the stem both in radial as well as in the vertical direction. Compression properties in all three palms vary along the trunk diameter (Figure 58). They are closely related with density and, thus, with the distribution of parenchymatous and sclerenchymatous tissues. The Figures 58 show the relationship between compression properties (MOR and MOE) and sample position along the trunk diameter in (coconut, oil and date palm) wood.

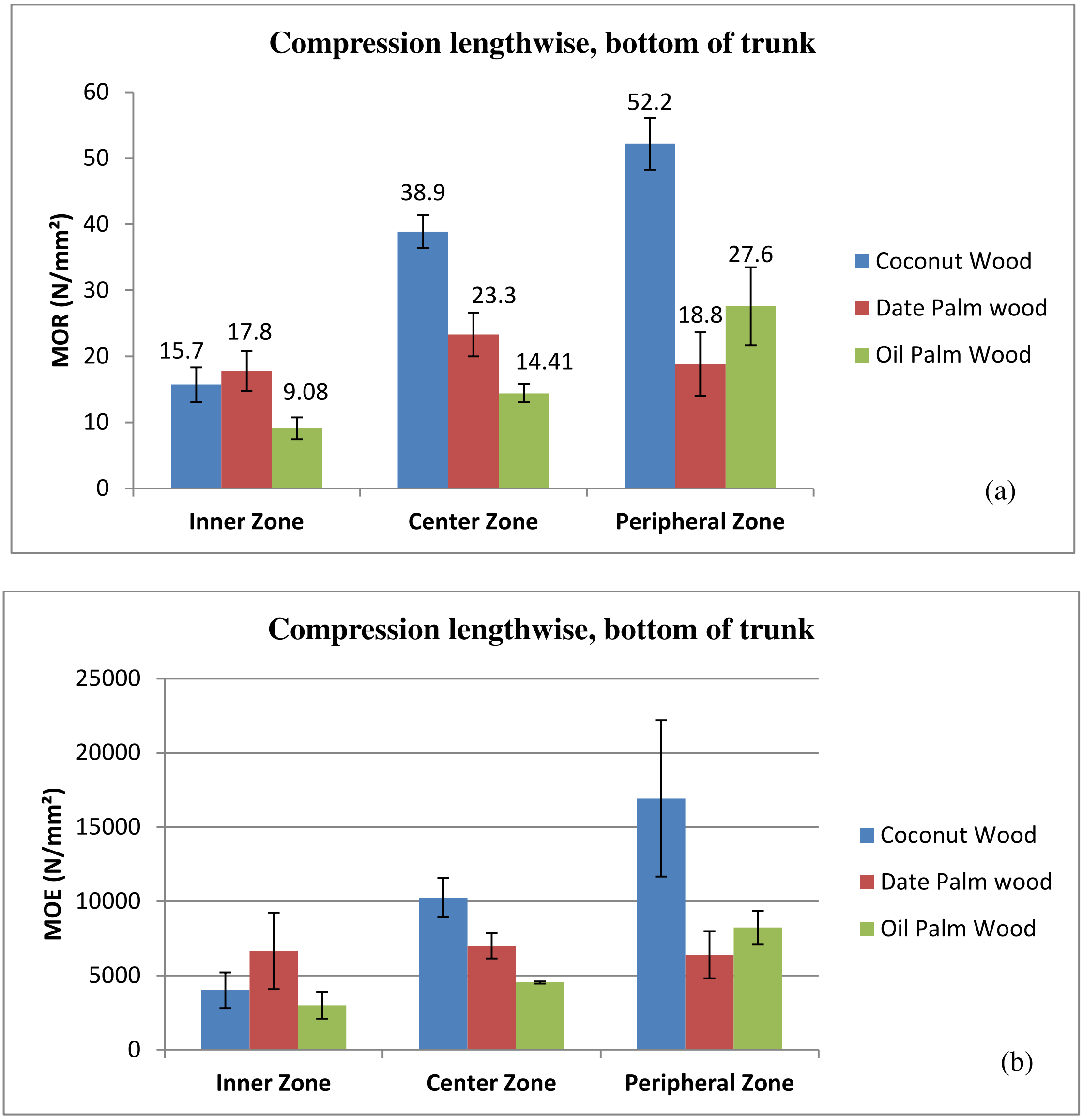


Figure 58. Compression properties (MOE/MOR) against sample position along the trunk diameter (coconut, date and oil palm wood)

Compression properties at given positions of coconut palm exceed by far (with one exception for MOE) those of date and oil palm stems. The highest values are obtained from the peripheral lower portion of the coconut stem. This is due to the generally higher percentage of denser tissues in coconut palms compared with date and oil palms (Killmann and Wong 1988).

As mentioned before, the physical and the mechanical properties (density, MOE, MOR, shear strength, nail and screw holding capacity, etc.) define the use of the timber for structural and non-structural purposes. Influenced by the remarkably high MOE/MOR values for the VBs (coconut 25000/350, oil palm 17500/240 and date palm 17000/280 N/mm²) wood

MOE and MOR in tension, compression and bending is high for peripheral zones of the stem. The maximum number of VB is 288 per 400 mm² of the wood having about 40% of total area of VB on the cross section of. Number and total area of VB have proven to be good indications for both density and most mechanical properties (see chapter 5.3.1). Based on the structure of the wood (parenchyma tissue and VB as reinforcing structure elements), shear strength is lower compared to common timbers. Splitting behavior and nail holding is also lower. Screw holding is high because of anchorage of the screw between the VB.

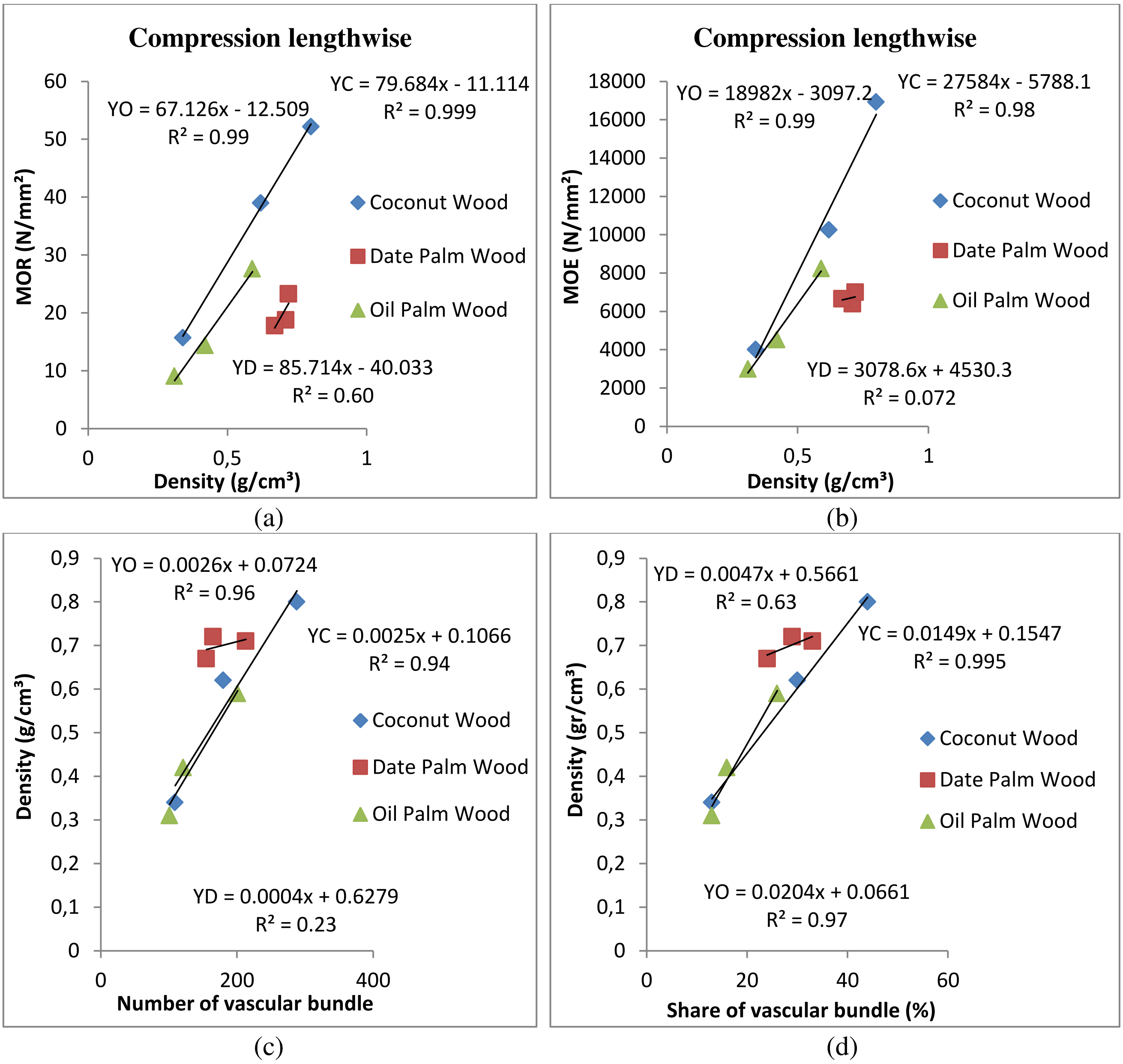


Figure 59. Relationships between: wood density and compression strength parallel to grain MOR (a) and MOE (b), (c) wood density and number of VB, (d) wood density and share of VB, (coconut, date and oil palm)

Table 40 shows some results compared to common wood species.

Table 40. Physical and mechanical properties of the coconut wood from different palms and common timbers (Fathi and Frühwald 2014)

Tree		Density (g/cm³)	Compression test lengthwise (mean values)		Shear strength (N/mm²) (mean values)
			MOR (N/mm²)	MOE (N/mm²)	
Coconut palm	MD	0.69	55	12800	9.4
	HD	0.92	81	19200	12.1
Oil palm	MD	0.42	14	4500	2.0
	HD	0.59	28	8200	3.7
Date palm	MD	0.67	15	4300	1.5
	HD	0.72	21	7500	1.5
Spruce [1)]		0.47	60	9500	6.5
Pine [1)]		0.52	85	10500	8.0
Oak [1)]		0.70	80	12000	11.0

[1)]Kollmann (1951) (average values)

From Table 40, it obvious that compression strength of oil palm wood is generally poor compared to coconut wood and other timber species but is comparable to date palm wood. Although oil palm stems is inferior to many other timber species, the compression value is comparable to rubber wood at similar density values (Killmann and Lim 1985).

In general, the compression strength results of the oil palm wood as well as the date palm wood over the cross section of the stem show that the values are similar but are lower than coconut wood.

These results can be explained by the anatomical structure of palm wood. In the base of the stem of coconut wood, there are much more congested VBs with sclerotized fibrous cap cells than in oil and date palm wood.

5.4.2 Coconut wood (Indonesia): Shear parallel to grain

118 specimens from boards 1, 4, 8 were tested to determine the range of shear strength values. The measured shear strength varied from 4.20 MPa to 23.99 MPa. The average test results are summarized in Table 41.

Table 41. Coconut wood (Indonesia): Shear parallel to grain, 12 % mc

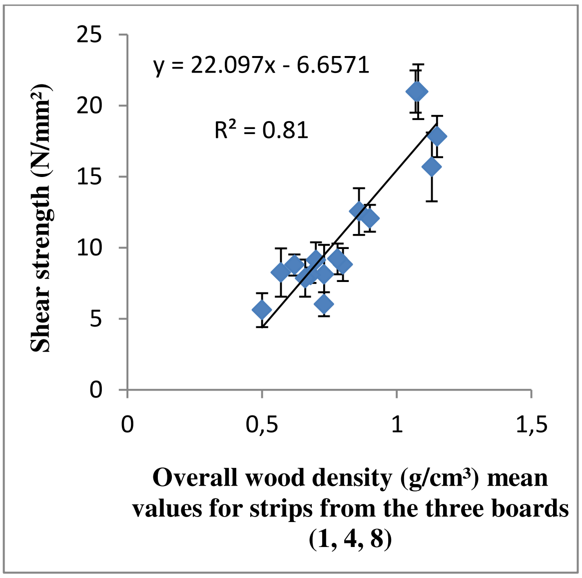
No. of board	No. of specimen	Average density (g/cm³)	Average shear strength (N/mm²)
1	32	1.11 (0.04)	19.03 (2.32)
4	51	0.79 (0.07)	9.36 (2.26)
8	35	0.61 (0.07)	7.71 (1.22)

Values in parentheses are standard deviation.

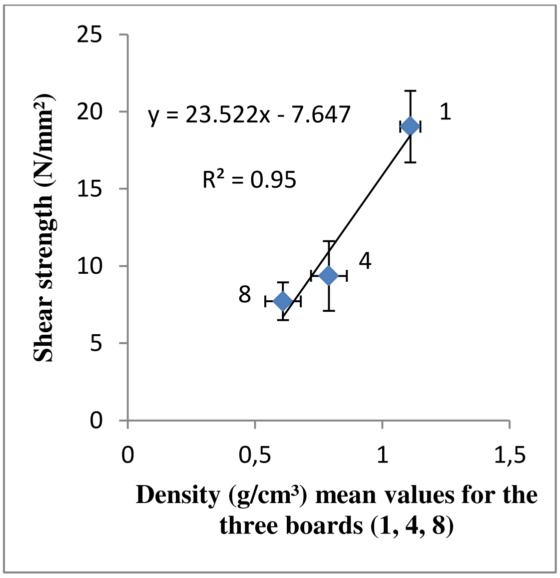
Shear results appear to be governed primarily by density which is demonstrated by a close statistical relationship (Figure 60). A change in shear strength between outer and inner zone is what would be predicted from the change in density using a published shear-density relationship for soft woods (Forest Products Laboratory 1999).

Figure 60a, b and c gives the summary of correlation coefficients between shear strength and wood density, density of parenchyma and density of VBs in the coconut wood. The values for density of VB and parenchyma are described in Table 32, chapter 5.2.6.

Correlation between shear strength and density of parenchyma (R^2= 0.95) is higher than correlation between shear strength and overall density (R^2= 0.81) and density of vascular bundle (R^2= 0.64; Figure 60). Thus, shear strength is closely related to the density of parenchyma or shear strength is mainly influenced by the density of parenchyma.



(a₁)



(a₂)

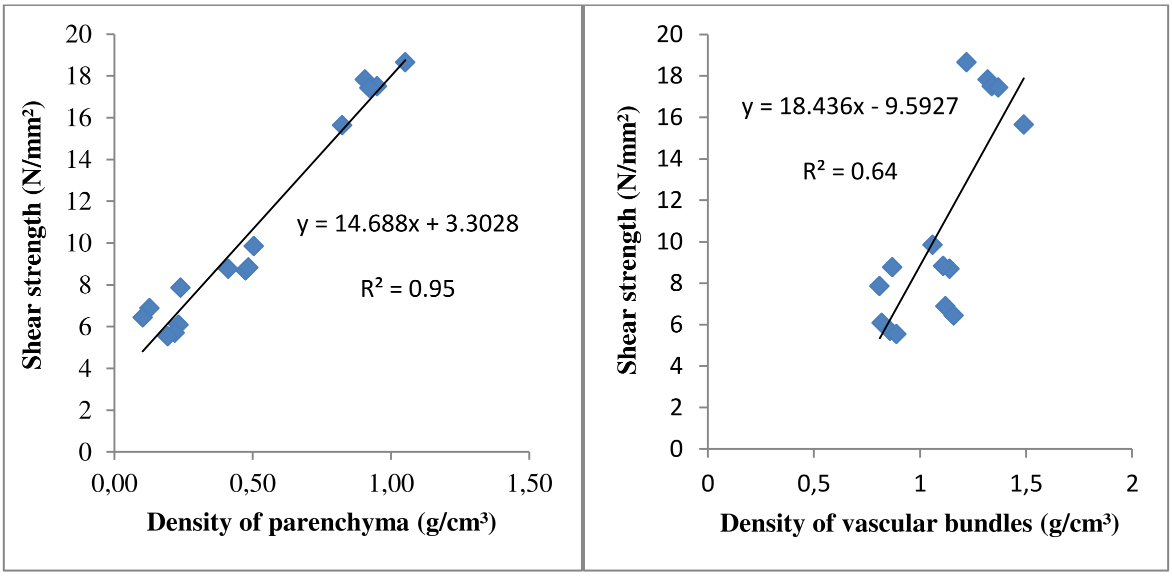


Figure 60a, b and c. Coconut wood (Indonesia): Relationship between shear strength and wood density, parenchyma, density and density of vascular bundles

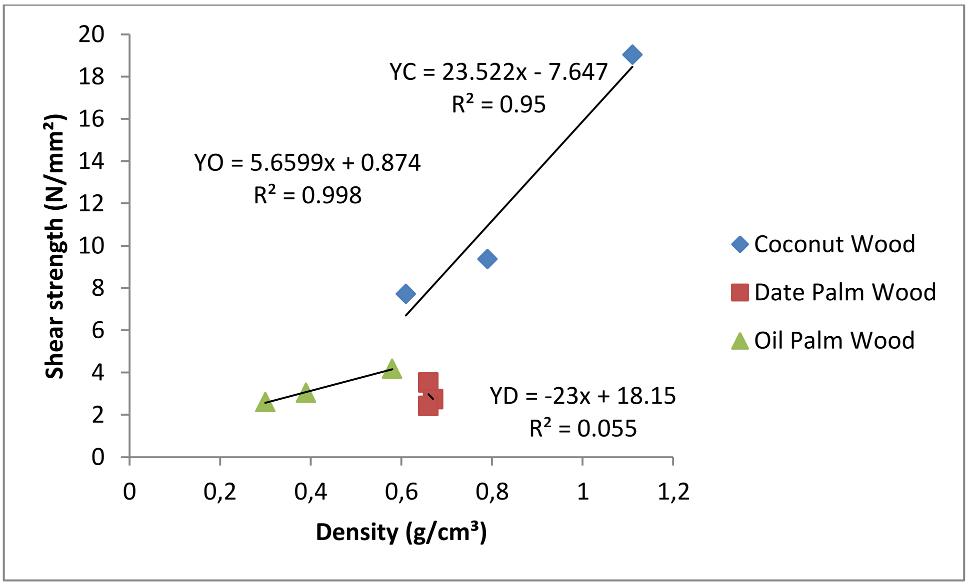


Figure 61. Shear strength against density (coconut, date, oil palm)

5.4.3 Coconut wood (Indonesia): Tension perpendicular-to-grain

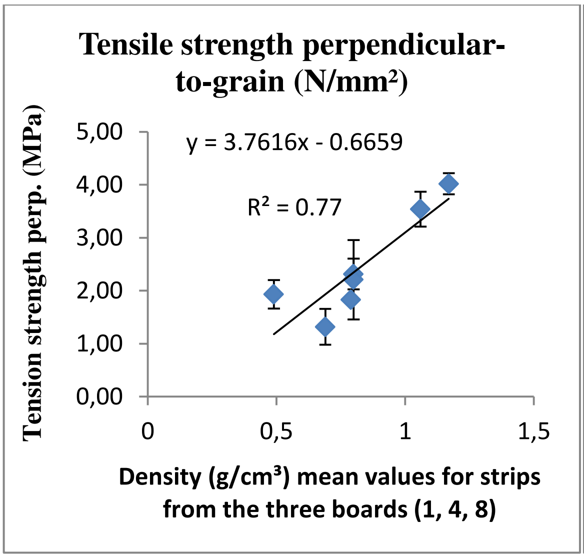
124 specimens were tested to determine the range of tension strength values perpendicular to the grain. The strength values were calculated as the ultimate load divided by the area. The size and the shape of samples are described in chapter 4.2.2.2.4. The measured strength values ranged from 0.93 MPa to 4.63 MPa. The average results for tension perpendicular-to-grain are summarized in Table 42.

Table 42. Coconut wood (Indonesia): Tension perpendicular-to-grain, 12 % moisture content

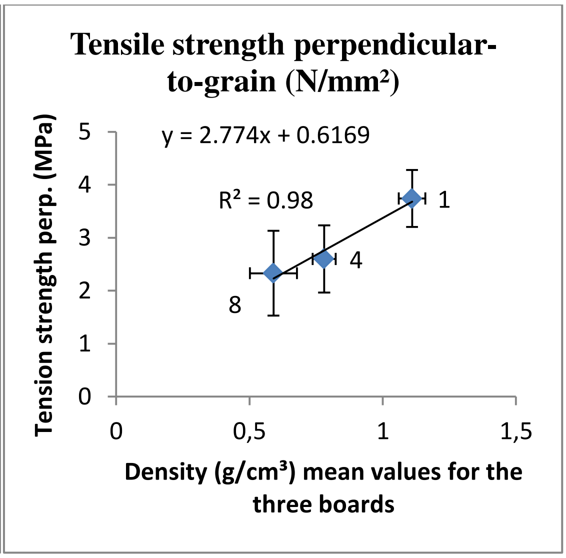
Sample no.	No. of specimen	Average density (g/cm³)	Average tension strength (N/mm²)
1	36	1.11 (0.05)	3.74 (0.54)
4	53	0.78 (0.04)	2.60 (0.63)
8	35	0.59 (0.09)	2.33 (0.80)

Values in parentheses are standard deviation.

The tension perpendicular-to-grain strength results showed a relatively small variation but are closely related to the density. The maximum single value of 4.63 MPa was found at the high density palm wood and the loads applied in the radial direction as well as any difference between radial and tangential, in general terms. The tension perpendicular strength decreased with decreasing density. Figure 62 gives the summary of correlation coefficients between the tension strength perpendicular-to-grain and the density of the coconut wood.



(a₁)



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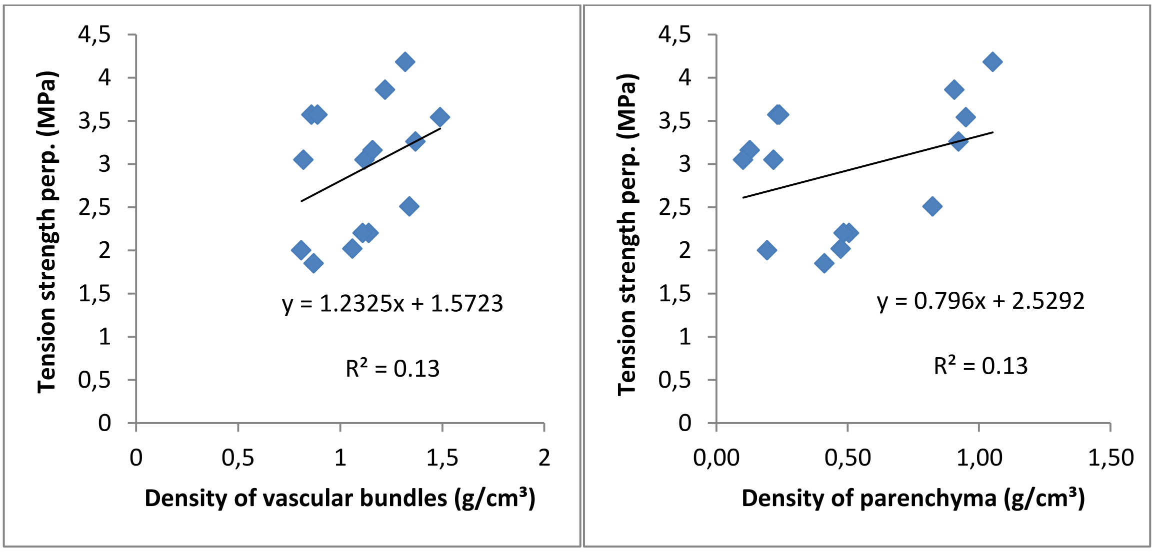


(b) (c)

Figure 62. Coconut wood (Indonesia): The relationship between tension strength perpendicular-to-grain density of parenchyma, overall wood density and density of VBs

5.4.4 Coconut wood (Indonesia): Tension parallel-to-grain

Forty specimens were tested. The measured strength values ranged from 26.48 MPa to 63.34 MPa. In Figure 63, the parallel tension strength values were grouped into a range of 10 MPa to obtain the distribution. The strength values obtained from the testing are shown in Table 43.

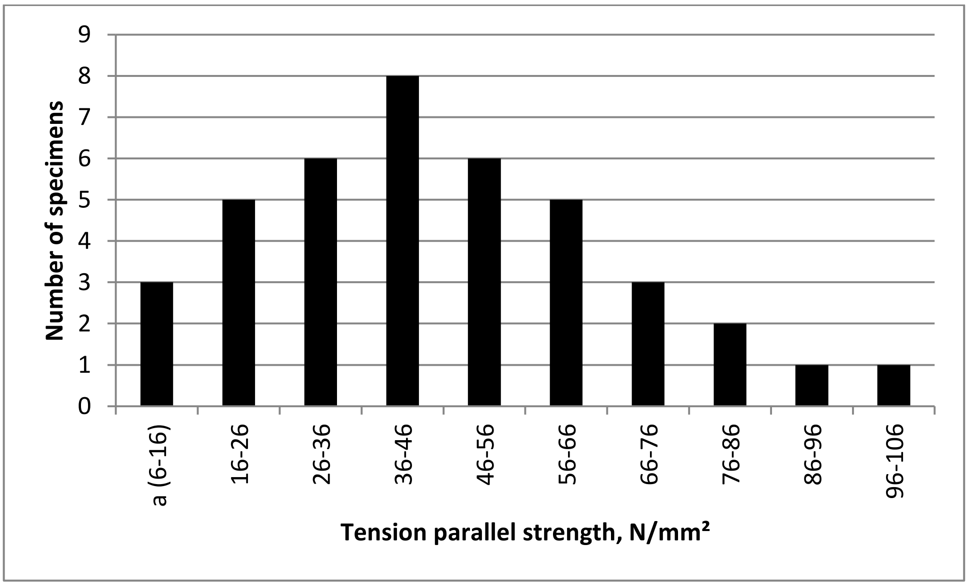


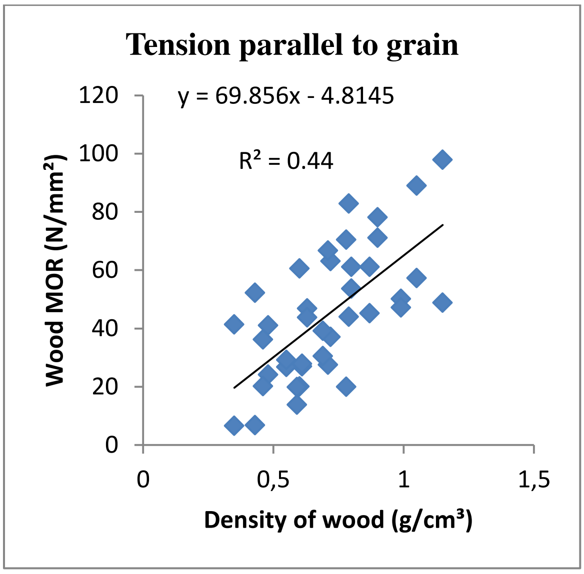
Figure 63. Coconut wood (Indonesia): Distribution of tension parallel strength

Table 43. Coconut wood (Indonesia): Tension parallel to grain, N/mm²

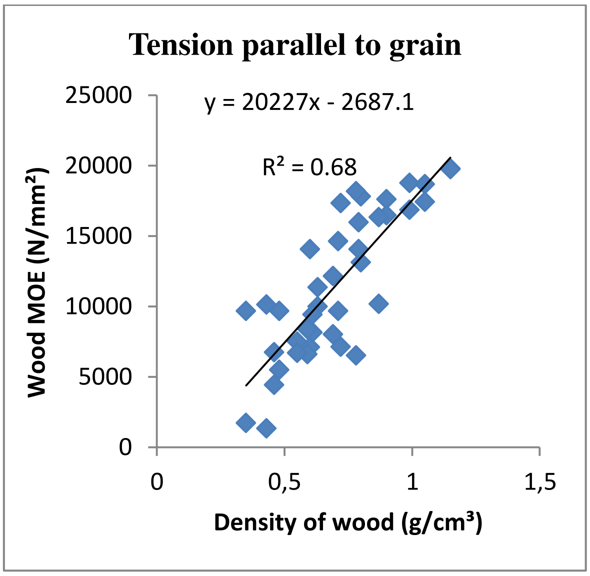
Board no.	No. of specimen	Average density (g/cm³)	Test results Avg MOR	Test results Avg MOE
2	12	0.96 (0.12)	63 (17.2)	16900 (2774)
5, 7	16	0.69 (0.07)	44 (19.3)	11485 (3817)
9, 10, 12	12	0.48 (0.08)	26 (14.25)	6530 (2902)

Values in parentheses are standard deviation.

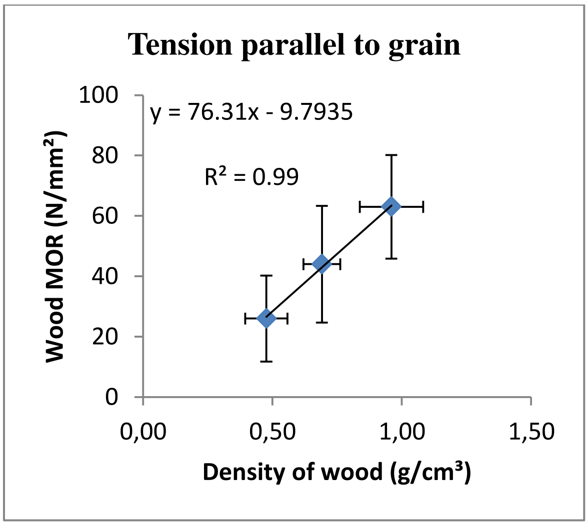
Figure 64 gives the summary of correlation coefficients between tension strength parallel-to-grain and overall density in the coconut wood.



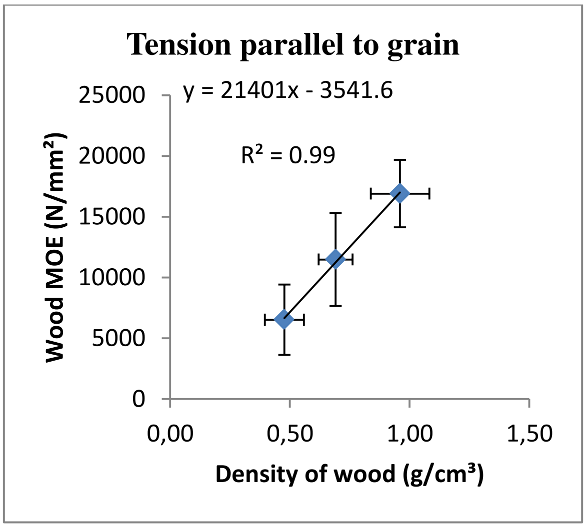
(a_1)



(b_1)



(a_2)



(b_2)

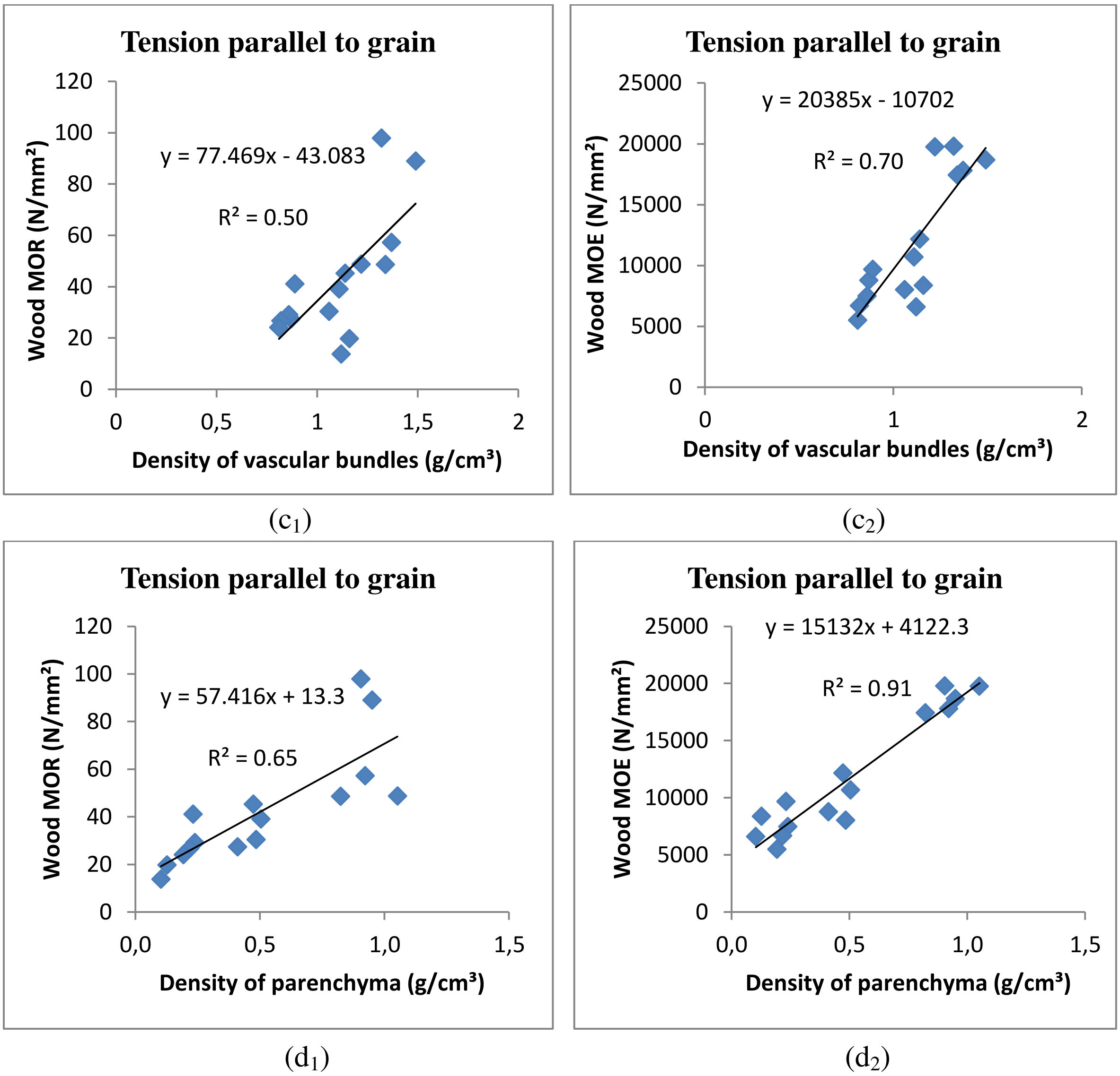


Figure 64. Coconut wood (Indonesia): MOR and MOE in tension parallel-to-grain for coconut (Indonesia). MOR (a_1) and MOE (b_1) of all coconut samples along trunk diameter, MOR (a_2) and MOE (b_2) of three densities (boards), relationship between MOR (c_1) and MOE (c_2) and density of vascular bundles, relationship between MOR (d_1) and MOE (d_2) and density of parenchyma

The results show that the correlation between wood tension strength and VB density is low. The reason might be the number of VB or the share (percentage) of VB. On the other hand, it was found that the samples had quite often slope of grain and, therefore, the failure occurred often along the slope because of low shear properties in the parenchyma (B_P= 0.91, B_{VB}= 0.70).

5.5 Property relationships

5.5.1 Effects of structure and density on strength properties of wood and of single vascular bundles

5.5.1.1 Coconut wood from Mexico (bottom of trunk)

The mechanical properties are shown in Figure 40 (tension properties of single VBs) and Figure 54 (tension properties wood). Table 44 gives the summary of correlation coefficients of mechanical properties and anatomical structure/physical properties.

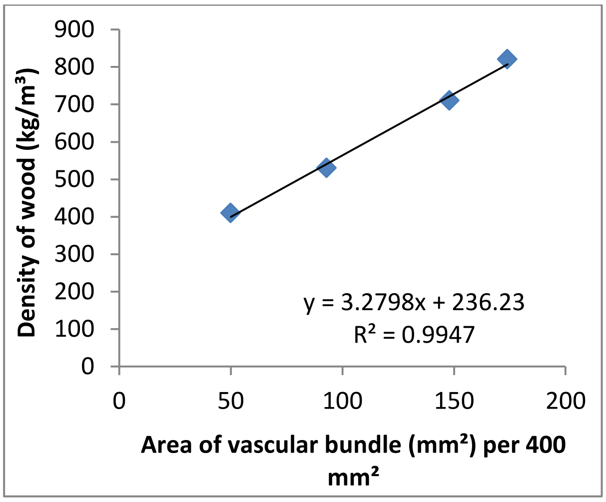
Table 44. Coconut wood (Mexico): Correlation coefficients between physical and mechanical properties and various anatomical structures

Properties	Tensile strength of VB	Compression parallel to grain
Total area of VB	0.87	0.99
Number of VBs	0.78	0.90
Cross-cut area of VB (measured with magic tool)	0.87	0.97
Diameter of VB	0.81	0.84
Density of wood samples	0.83	0.99
Compression parallel to grain	0.86	

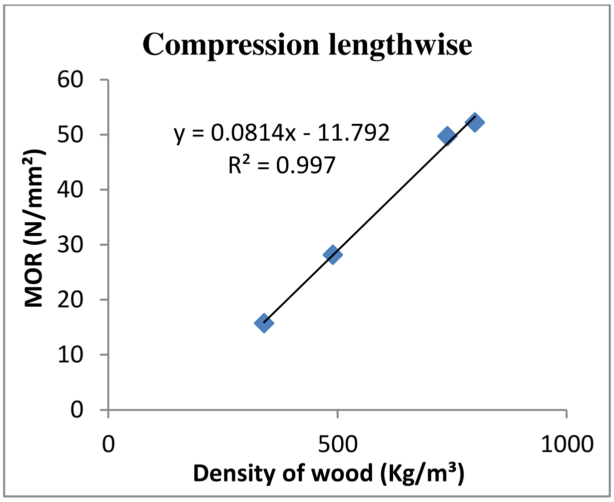
The correlation coefficients are not based on the fit using linear equation.

Figures 40 and 54 reveal that the compression parallel to the grain, the MOE and the tension parallel to the grain of single VB increase gradually with distance from the inner part of the trunk. The correlations presented in Table 44 can be rated as medium to strong.

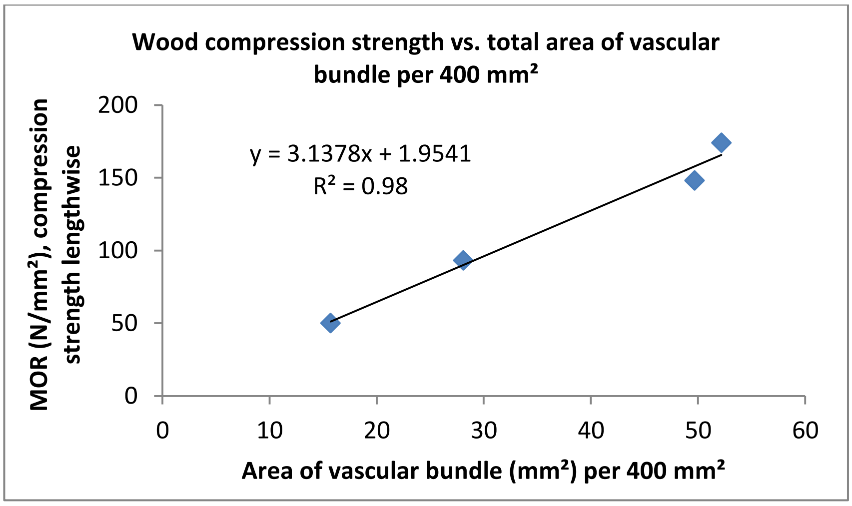
The density of coconut wood, which is closely related to the number and the area/volume of the VBs and the ground tissue, has an important role on mechanical properties. In Figure 65, it can be seen that first, the density of coconut wood depends strongly on the total area of VBs and second, the MOR of wood depends strongly on the density and the total area of VBs. Knowing the distribution of the total area (percentage of VB from total cross-cut area) of VBs, it is possible to model the density and the mechanical properties of coconut wood. These relationships can easily be used for grading lumber and for developing sawing patterns in the lumber processing. However, this model can only be established when the density of VB is constant. This can be assumed for the radial direction at a given height of the trunk. But as shown in chapter 5.2.6, the density of VB along the trunk height can vary significantly.



(a)



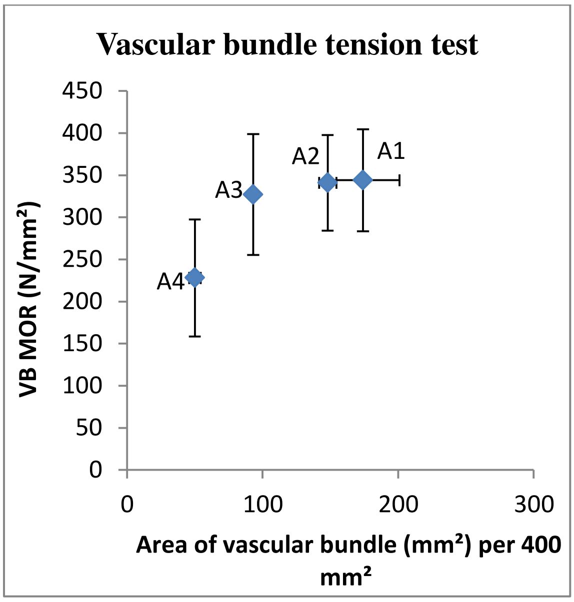
(b)



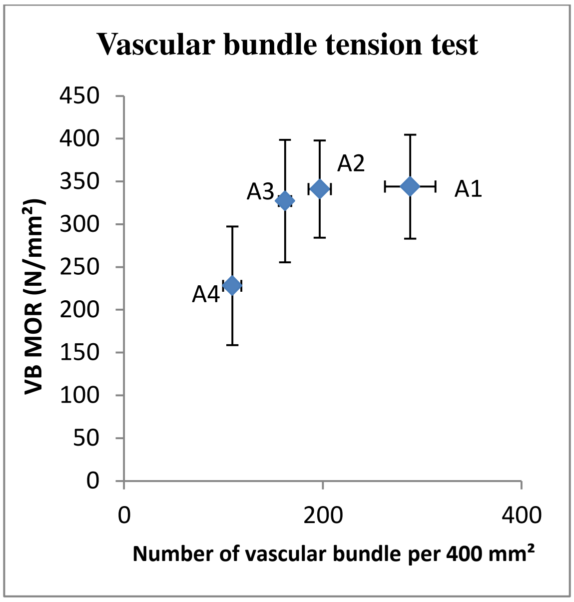
(c)

Figure 65. Coconut wood (Mexico): Relationships between (a) density of coconut wood and total area of vascular bundles, (b) wood density and compression strength parallel to grain, (c) compression strength parallel to grain and total area of VB

Further statistical analysis was conducted to evaluate the effects of physical and anatomical characteristics on the mechanical properties. Results are shown in Figure 66.



(a)



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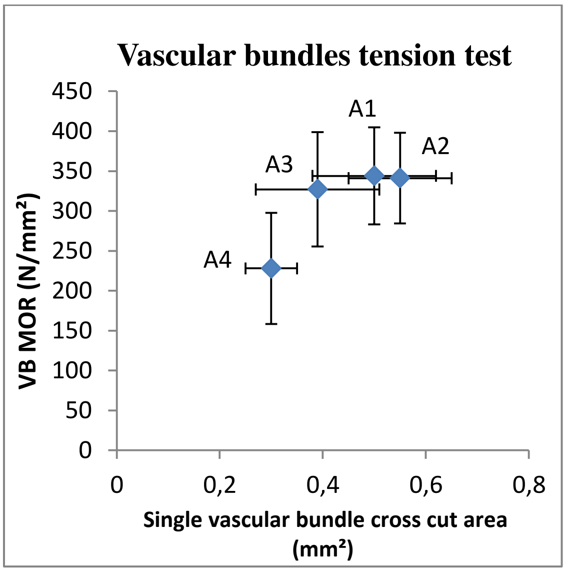

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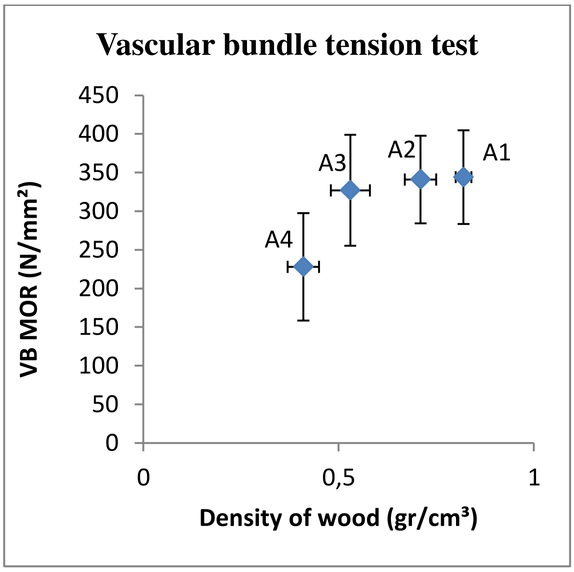

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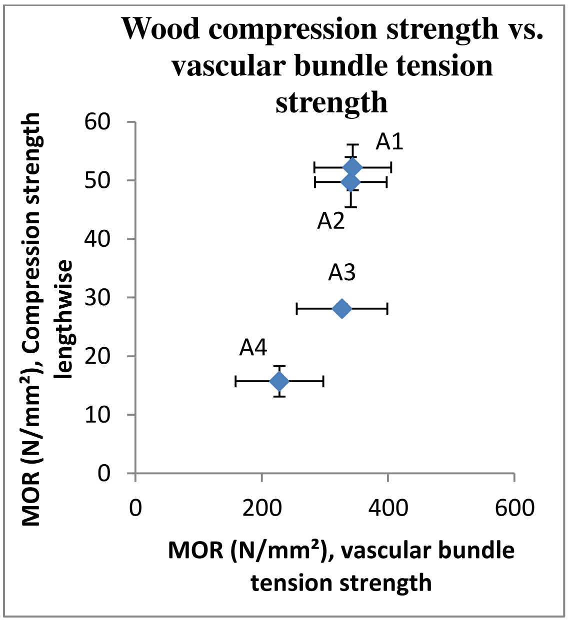
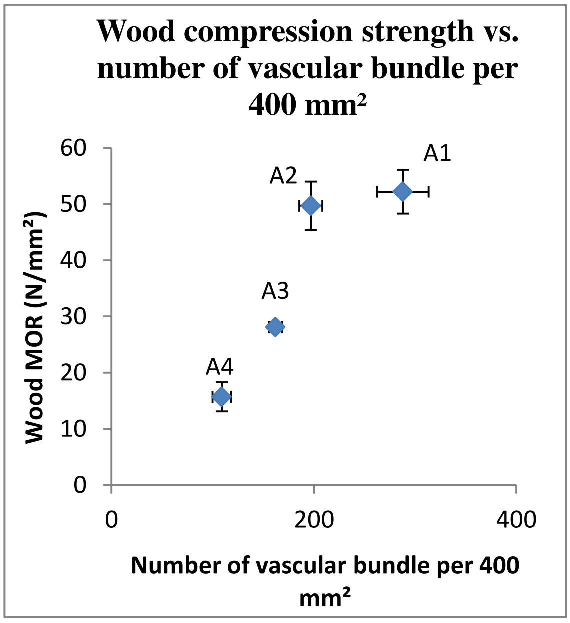


(e)



(f)

Figure 66. Coconut wood (Mexico): Effects of physical and anatomical characteristics on the mechanical properties of single vascular bundles. Relationships between: (a) tensile strength of VB and total area (percentage) of VBs, (b) tensile strength of VBs and number (frequency) of VBs, (c) tensile strength of VBs and square of VBs, (d) tensile strength of VBs and density of wood, (e) tensile strength of VBs and wood compressive strength parallel to grain, (f) wood compressive strength parallel to grain and number (frequency) of VBs

The analysis indicates that all properties, namely compression of wood parallel to grain, MOE and MOR in tension parallel to the grain of single VB, highly depend on the density and the location in the trunk. This implies that the density increase reflects a 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). The analysis further indicates that the area of VBs is closely correlated with all strength properties. Figure 66c shows the influence of single VB area on $MOR_{tension}$; smaller VB results in lower MOR. In small VB the share of vessels on the cross-cut area of VB is higher compared to the larger diameter VB. Thus, fiber cap share is higher in larger VB, which this results in higher MOR values. Figure 67 shows the relationship between volume fraction (vf) of VBs and MOR of wood in compression lengthwise. According to the regression, the MOR in the compression of VBs (calculated with 100% vf) is 125 MPa, which is about 40-50% of the results for MOR of VB in tension. This relation is similar to the well-known relation of the tension strength compared to the compression strength of 2:1, which can be found for most wood species (Kollmann 1951). The result implies that the increase in the amount of VBs is accompanied by the increment in the greater number of sclerenchyma and conducting cells and density and, thus, increases in the strength properties (Sulthoni 1989). VB diameter (tangential) is positively correlated with compression strength, MOE and tension strength of single VB. This indicates that an increase in tangential diameter of VBs is accompanied by an increment of strength properties. This is to explain by the increase of the share of fiber cap area in relation to the VB area if the diameter of VB increases (assumption is that the vessels are remaining more or less constant in size). The results also show that with increasing mechanical properties of single VB, strength properties of coconut wood increase.

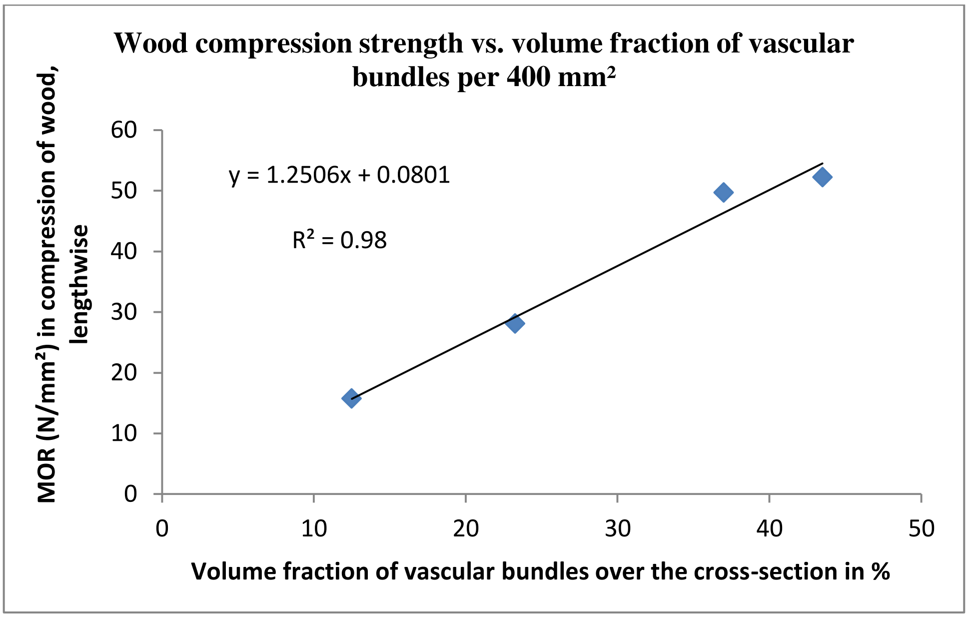


Figure 67. Coconut wood (Mexico): Relationship between compression strength parallel to grain and volume fraction of VBs over the cross-section

5.5.1.2 Oil palm wood (bottom, middle and top of trunk)

The mechanical properties are presented in Figure 43 (tension strength of single VBs) and Figure 56, compression properties of the oil palm wood. Table 45 gives the summary of correlation coefficients of mechanical properties and anatomical structure/physical properties of wood and VB.

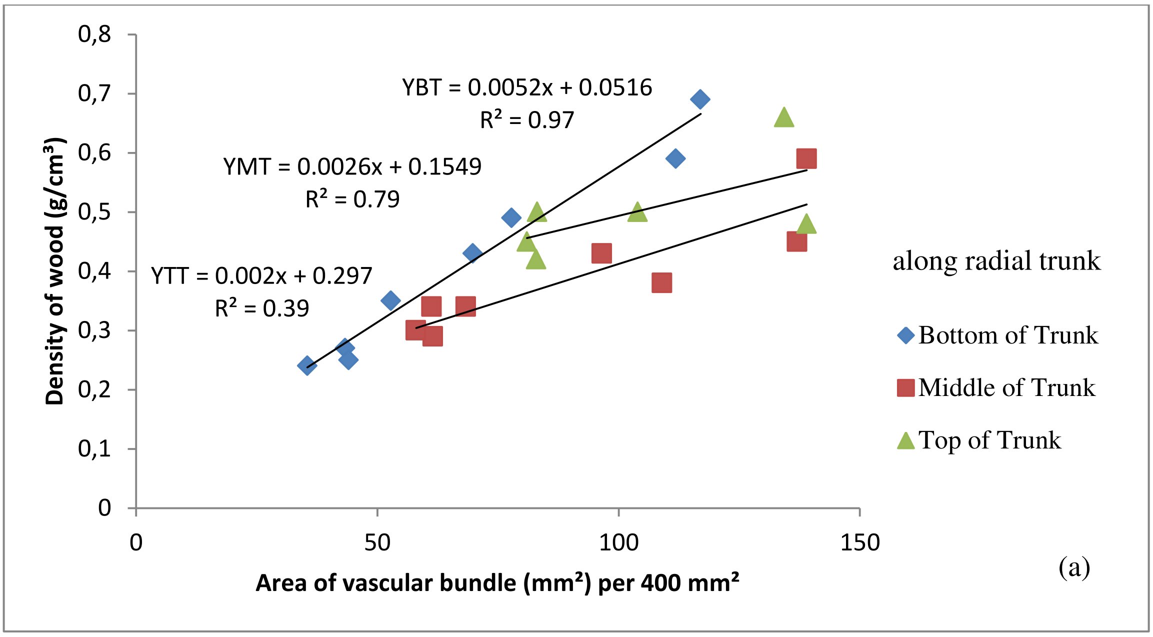
Table 45. Oil palm wood: Coefficients for the correlations between mechanical properties and anatomical/physical properties

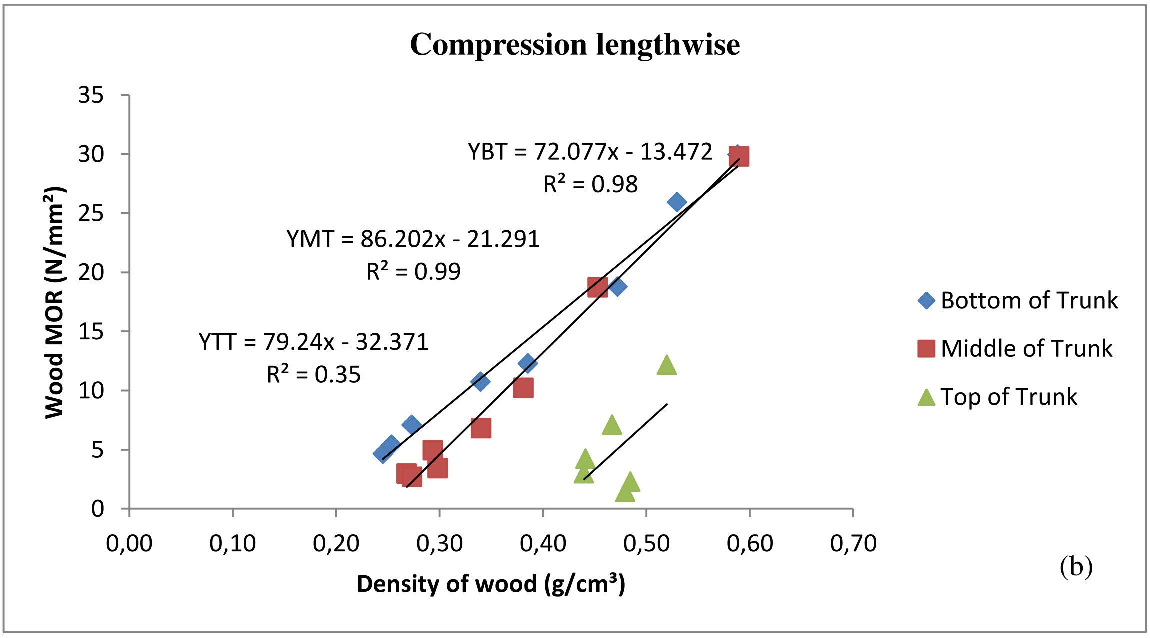
Properties	Trunk height	Tensile strength of VB		Compression parallel to grain			
		Bottom	Top		Bottom	Middle	Top
Total area of VB	Bottom	0.99		Bottom	0.99		
				Middle		0.99	
	Top		0.99	Top			0.85
Number of VBs	Bottom	0.99		Bottom	0.99		
	Top		0.99	Middle		0.99	
				Top			0.98
Cross-cut area of VB	Bottom	-0.95		Bottom	0.00		
	Top		-0.95	Middle		0.46	
				Top			-0.49
Diameter of VB	Bottom	-0.87		Bottom	0.96		
	Top		-0.90	Middle		0.35	
				Top			-0.51
Density of wood samples	Bottom	0.99		Bottom	0.99		
	Top		0.06	Middle		0.99	
				Top			0.94
Compression parallel to grain	Bottom	0.99					
	Top		0.99				

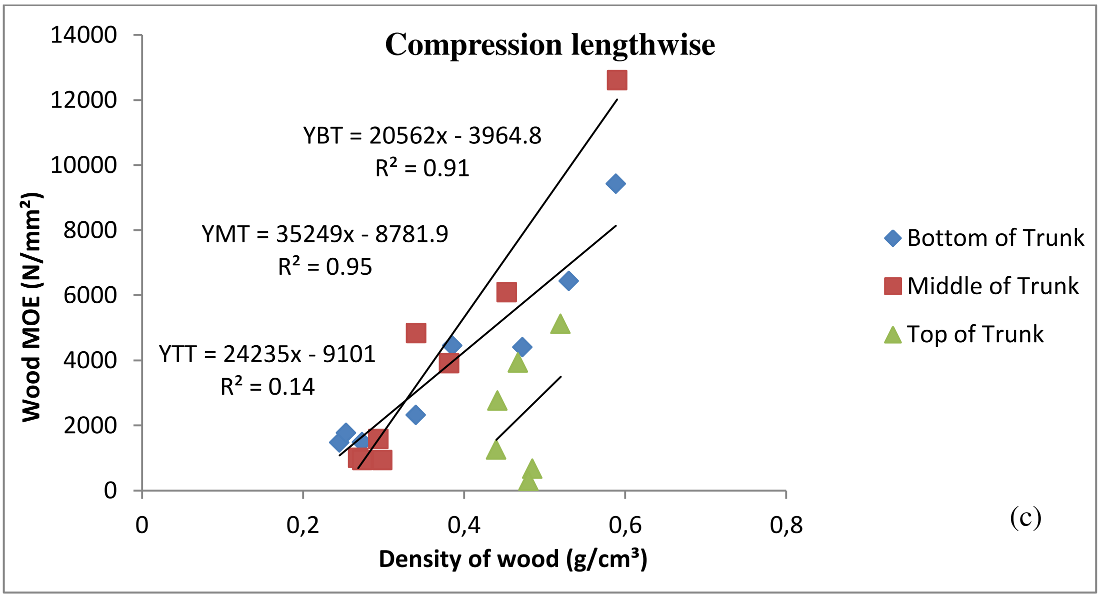
The correlation coefficients are not based on the fit using linear equation.

Figures 43 and 56 show wood-MOE in compression parallel to grain, and tension parallel to grain of single VB decrease gradually with distance from the peripheral to the inner zone of the trunk and also along the trunk height from the bottom to the top. The correlations are presented in Table 45. Similarly as for coconut wood (compare 5.2.5), the density of oil palm wood, which depends the properties of VBs and ground tissue, has an important effect on the mechanical properties. Figure 68 shows that the density of oil palm wood at the bottom and the middle of the trunk depend strongly on the total area of VBs and second, the MOR of wood in the bottom and middle of tree depends strongly on the density and the total area of VBs. Knowing the distribution of the total area (percentage of VB from total cross-cut area) of VBs, it is possible to model density and mechanical properties of oil palm wood at the bottom and the middle of tree. These relationships can easily be used for grading lumber and for developing sawing patterns in lumber processing at the bottom and middle of trunk. However, the statistical evaluation revealed a weak correlation (R^2= 0.39 between density and total area of VBs, R^2= 0.35 between the MOR of wood and density, and R^2= 0.07 between the

MOR of wood and total area of VBs) at the top of tree. These results suggest that other parameters are also effective; mainly the parenchyma tissue, the chemical composition of wood, i.e. lignin, cellulose and hemicellulose and the other anatomical parameters, i.e. proportion of fibers in a vascular bundle, cell wall thickness, and microfibrillar angle in the cell wall layers.







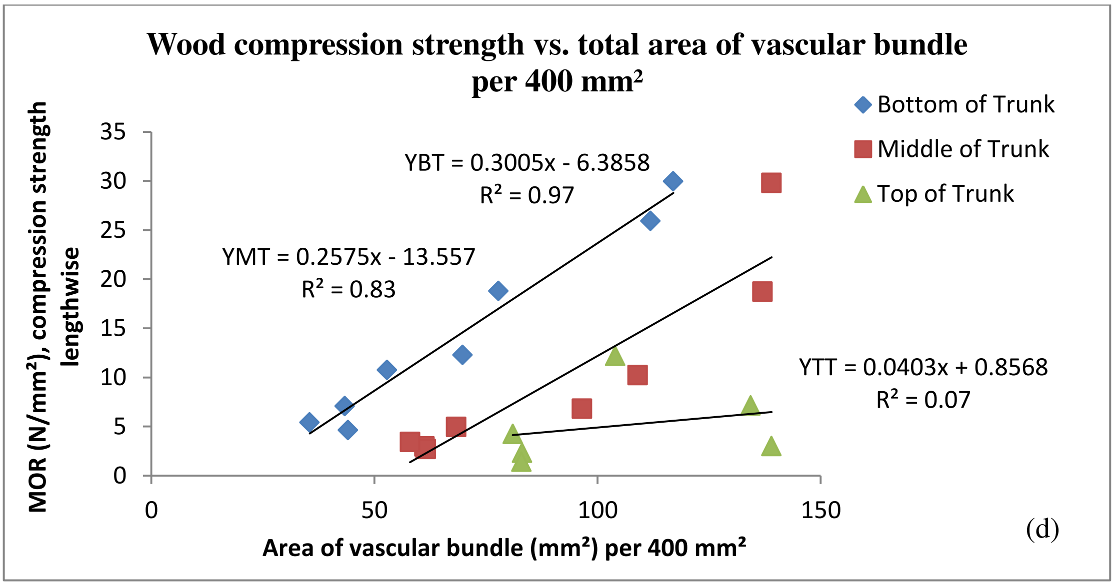
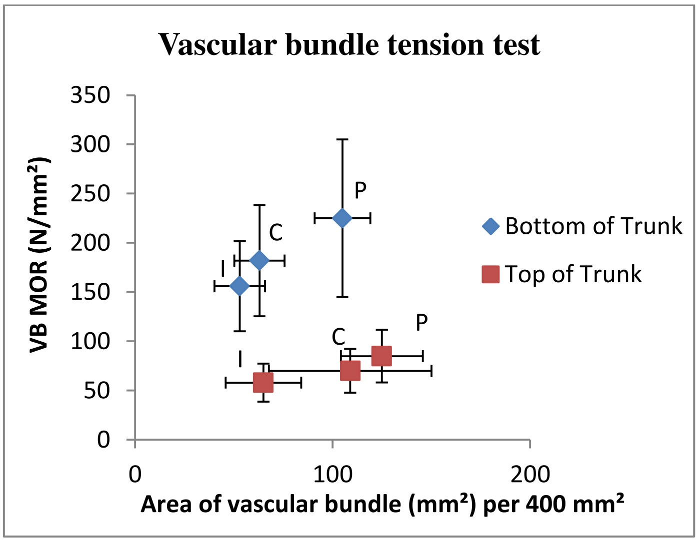


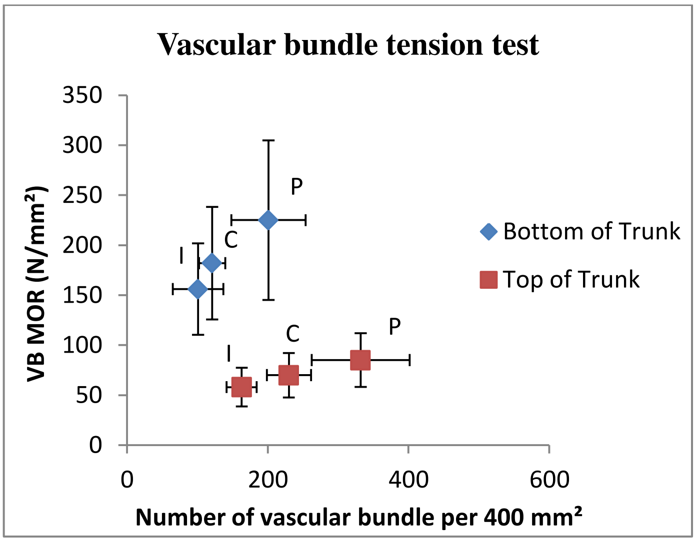
Figure 68. Oil palm wood: Relationships between (a) density oil palm wood and total area of vascular bundles, wood density and compression strength parallel to grain MOR (b) and MOE (c), (d) compression strength parallel to grain and total area of VB

Further statistical analysis was conducted to evaluate the effects of physical and anatomical characteristics on the mechanical properties. The results are shown in Figure 69.



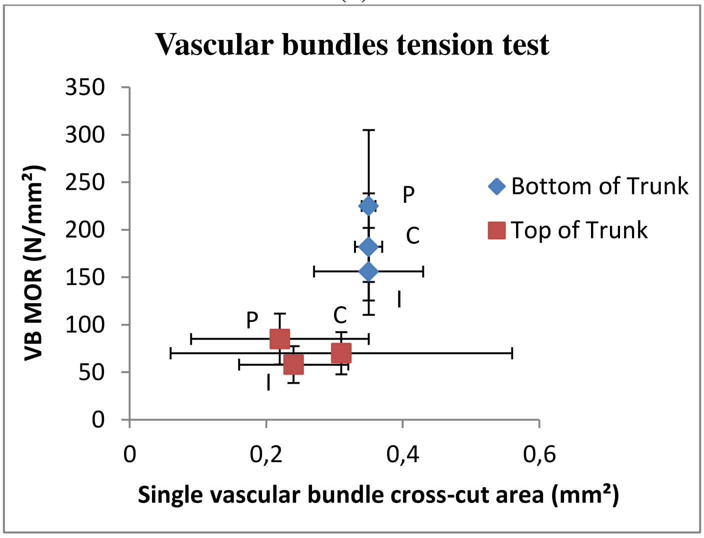
Vascular bundle tension test
VB MOR (N/mm²)
Area of vascular bundle (mm²) per 400 mm²
350
300
250
200
150
100
50
0
0
100
200
P
C
I
Bottom of Trunk
Top of Trunk

(a)



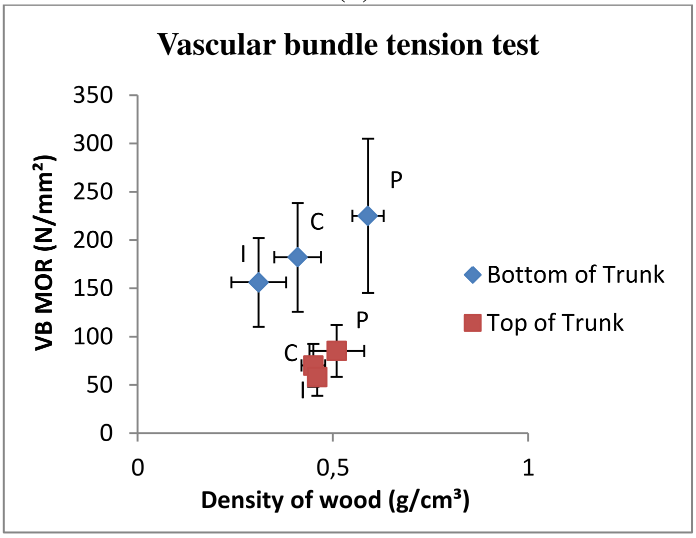
Vascular bundle tension test
VB MOR (N/mm²)
Number of vascular bundle per 400 mm²
350
300
250
200
150
100
50
0
0
200
400
600
P
C
I
Bottom of Trunk
Top of Trunk

(b)



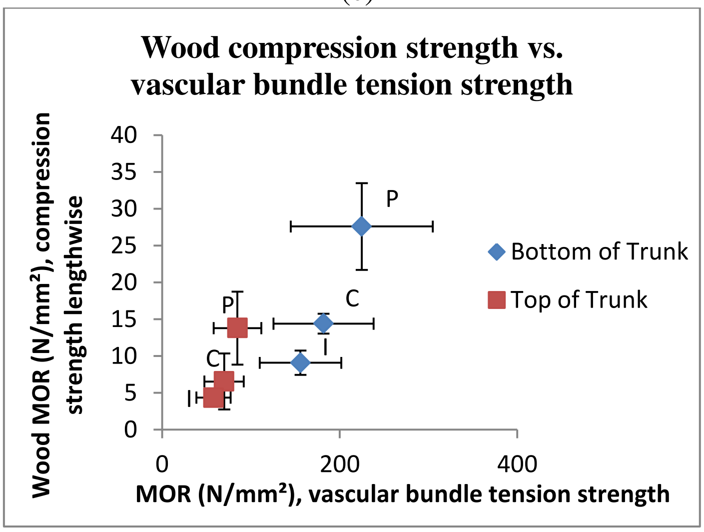
Vascular bundles tension test
VB MOR (N/mm²)
Single vascular bundle cross-cut area (mm²)
350
300
250
200
150
100
50
0
0
0,2
0,4
0,6
P
C
I
Bottom of Trunk
Top of Trunk

(c)



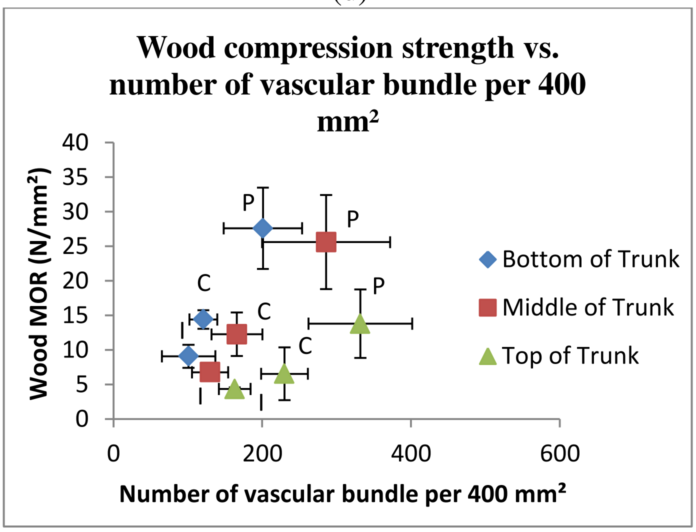
Vascular bundle tension test
VB MOR (N/mm²)
Density of wood (g/cm³)
350
300
250
200
150
100
50
0
0
0,5
1
P
C
I
Bottom of Trunk
Top of Trunk

(d)



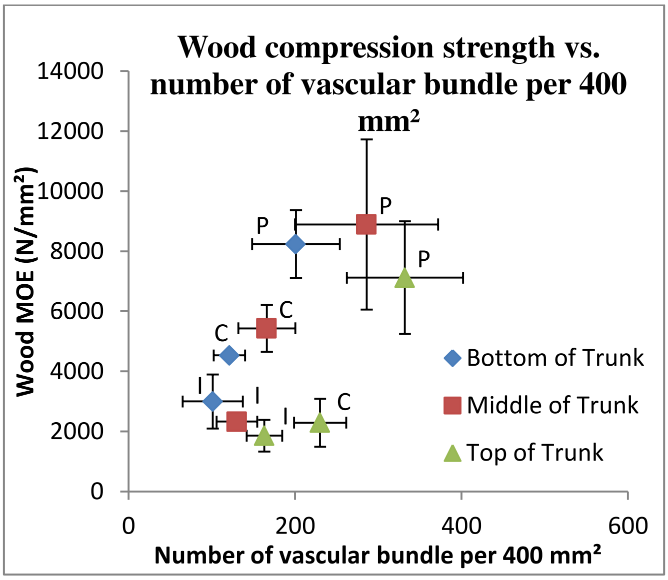
Wood compression strength vs. vascular bundle tension strength
Wood MOR (N/mm²), compression strength lengthwise
MOR (N/mm²), vascular bundle tension strength
40
35
30
25
20
15
10
5
0
0
200
400
P
C
I
Bottom of Trunk
Top of Trunk

(e)



Wood compression strength vs. number of vascular bundle per 400 mm²
Wood MOR (N/mm²)
Number of vascular bundle per 400 mm²
40
35
30
25
20
15
10
5
0
0
200
400
600
P
C
I
Bottom of Trunk
Middle of Trunk
Top of Trunk

(f)



(g)

Figure 69. Oil palm wood: Effects of physical and anatomical characteristics on the mechanical properties of wood and single vascular bundles. Relationships: (a) tensile strength VB and total area (percentage) of VBs, (b) tensile strength VBs and number (frequency) of VBs, (c) tensile strength of VBs and single VB cross area, (d) tensile strength VBs and density of wood, (e) tensile strength VBs and wood compressive strength parallel to grain, wood compressive strength parallel to grain and number (frequency) of VBs, MOR (f), MOE (g); P is near "the bark" of the trunk (peripheral), C is in between outer and inner zones (central) and I is near the core of the trunk (inner)

The analysis indicates that properties such as compression parallel to grain at the bottom and the middle of the trunk are strongly correlated (R^2= 0.98 bottom of trunk, R^2= 0.99 middle of trunk) whereas MOE and MOR in tension parallel to grain of single VBs at the bottom of trunk have a lower correlation (R^2= 0.67). However, the statistical evaluation revealed a weak correlation (R^2= 0.35) between compression parallel to grain and density of wood. This is not comparable to common timber species, where mostly, a strong correlation is found. One explanation for palm wood might be that the VB tend to buckle when loaded lengthwise. The parenchyma between the VB is very sensitive to the loading perpendicular to grain. A value R^2=0.11 between MOR (tension parallel to grain of single VBs) and density of wood at the top of trunk is extremely low, which imply that other parameters are more effective; mainly generally higher percentage of denser tissues at the bottom and the middle of trunk compared with the top of trunk.

Figure 70 shows the relationship between volume fraction (vf) of VBs and MOR/MOE of wood in compression lengthwise. The analysis of Figure 70 indicates that the percentage of

VBs has a high influence on all strength properties at the bottom and the middle part of the trunk, but not at the top of the trunk. This again leads to the previous conclusion that the smaller diameter VB at the trunk top has a much reduced fiber cap and a less reduced vessel area compared to VB at the lower heights of the trunk. This reduces density and as a result the strength of VB.

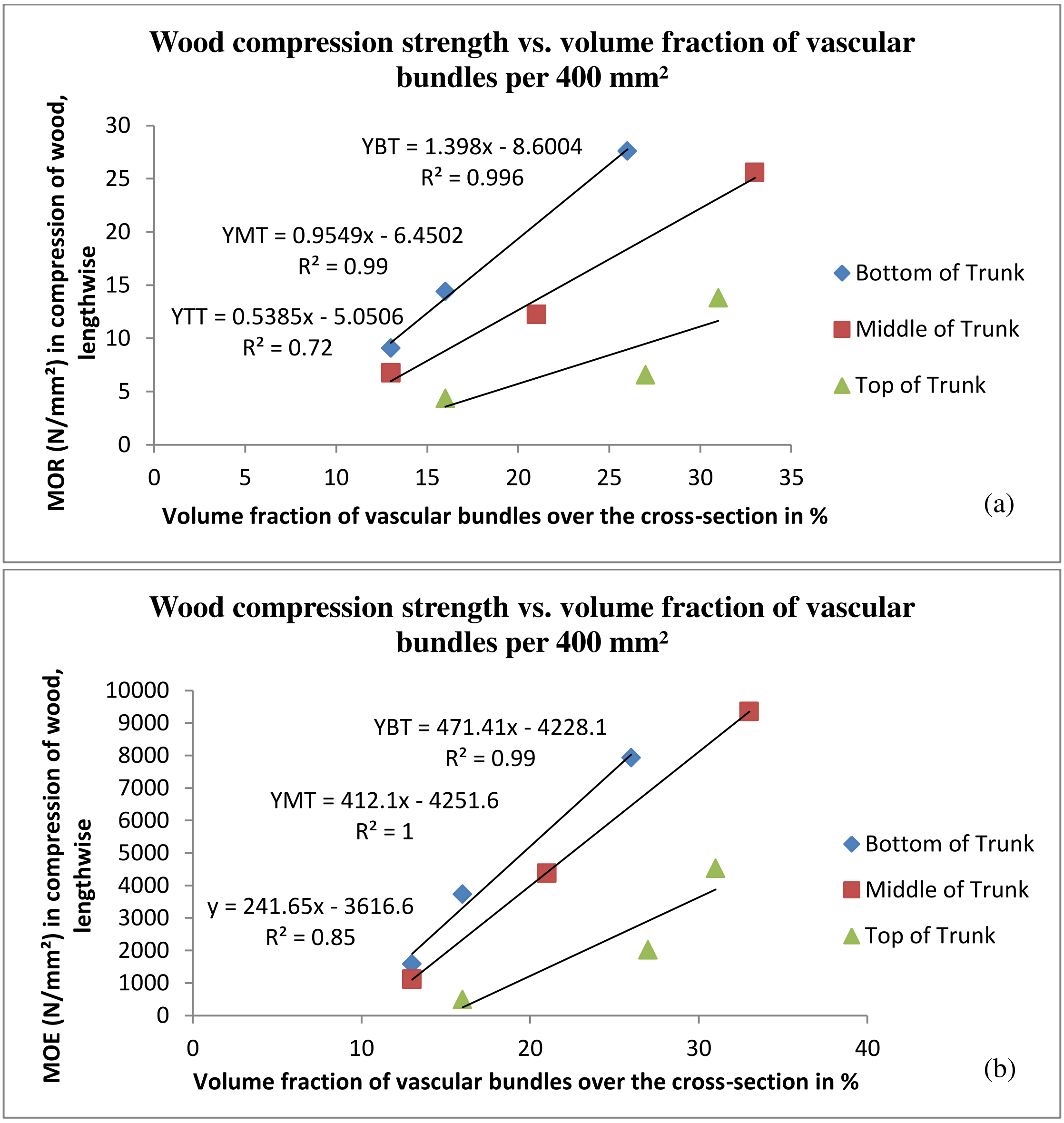


Figure 70. Oil palm wood: Relationship between compression strength parallel to grain and volume fraction of vascular bundles over the cross-section, MOR (a) and MOE (b)

In the theory of composite, volume fraction of fiber (vf), which can be calculated from the total area of VBs, is a crucial factor in determining the mechanical strength of the composite. This might be also true for this case here. According to the regression, the MOR of VBs in the compression (calculated with 100% vf) is around 131 MPa at the bottom of trunk, 89 MPa in the middle of trunk and 49 MPa at the top of trunk. This value is about 40-50% of the results for MOR of VB in tension. This implies that the increase in the amount of the VBs is accompanied by the increment in the greater number of sclerenchyma and conducting cells and density and, thus, increases in the strength properties (Sulthoni 1989). Strength in the compression is lower than in the tension due to the buckling of fiber during the compression test, which is a pronounced failure mode due to a low density of parenchyma.

Vascular bundle diameter (tangential) is positively correlated with the compression strength. This indicates that an increase in the tangential diameter of VBs is accompanied by an increment of strength properties. The results also show that with the increasing mechanical properties of single VBs, strength properties of oil palm wood increase as well.

5.5.1.3 Date palm wood (bottom, middle and top of trunk)

The mechanical properties are presented in Figure 45 and Table 25 (tension strength of single VBs) and Figure 57 (date palm wood). Table 46 gives the summary of the correlation coefficients of the mechanical properties in relation to the anatomical structure and the physical properties of wood.

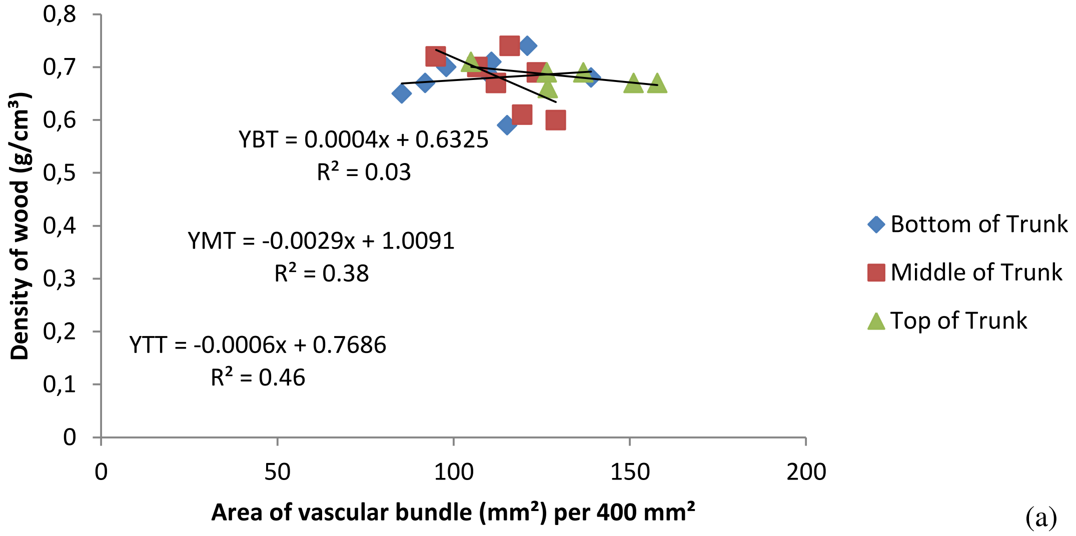
Table 46. Date palm wood: Correlations coefficients for the between mechanical properties and anatomical/physical properties

Properties	Trunk height	Tensile strength of VB		Compression parallel to grain			
		Bottom	Top		Bottom	Middle	Top
Total area of VB	Bottom	-0.84		Bottom	-0.32		
				Middle		0.35	
	Top		0.86	Top			-0.06
Number of VBs	Bottom	-0.999		Bottom	-0.72		
	Top		0.18	Middle		-0.64	
				Top			-0.69
Cross-cut area of VB	Bottom	0.40		Bottom	0.86		
	Top		0.31	Middle		0.87	
				Top			0.92
Diameter of VB	Bottom	0.34		Bottom	0.86		
	Top		0.30	Middle		0.90	
				Top			0.91
Density of wood samples	Bottom	0.75		Bottom	0.97		
	Top		-0.15	Middle		0.73	
				Top			0.67
Compression parallel to grain	Bottom	0.92					
	Top		0.74				

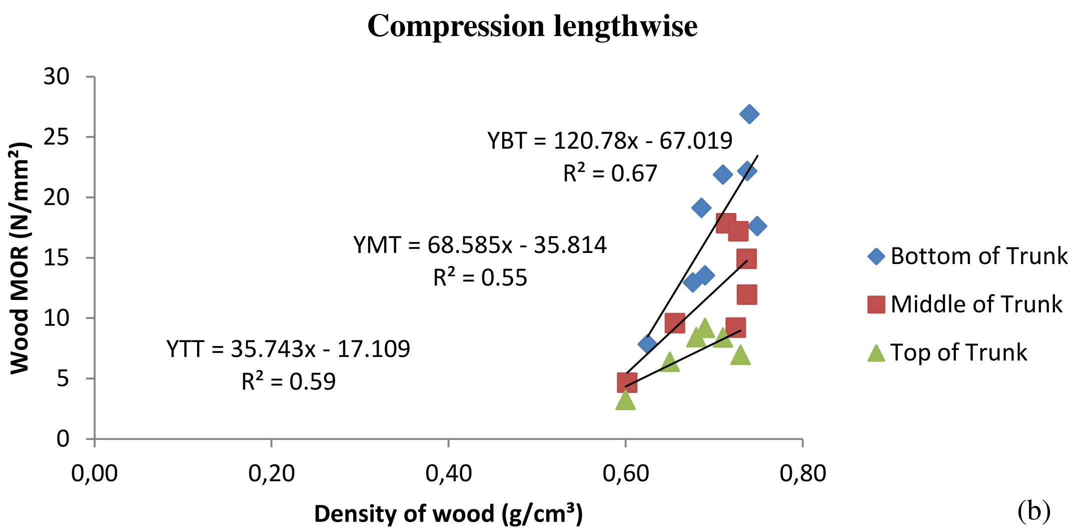
The correlation coefficients are not based on the fit using linear equation.

Figures 45 and 57 reveal that for compression of wood parallel to grain, the MOE and the tension (MOR) of single VB decrease slightly with distance from the outer zone to the inner zone of the trunk and also strongly along the trunk height from the bottom to the top. This is similar to oil palm but less pronounced.

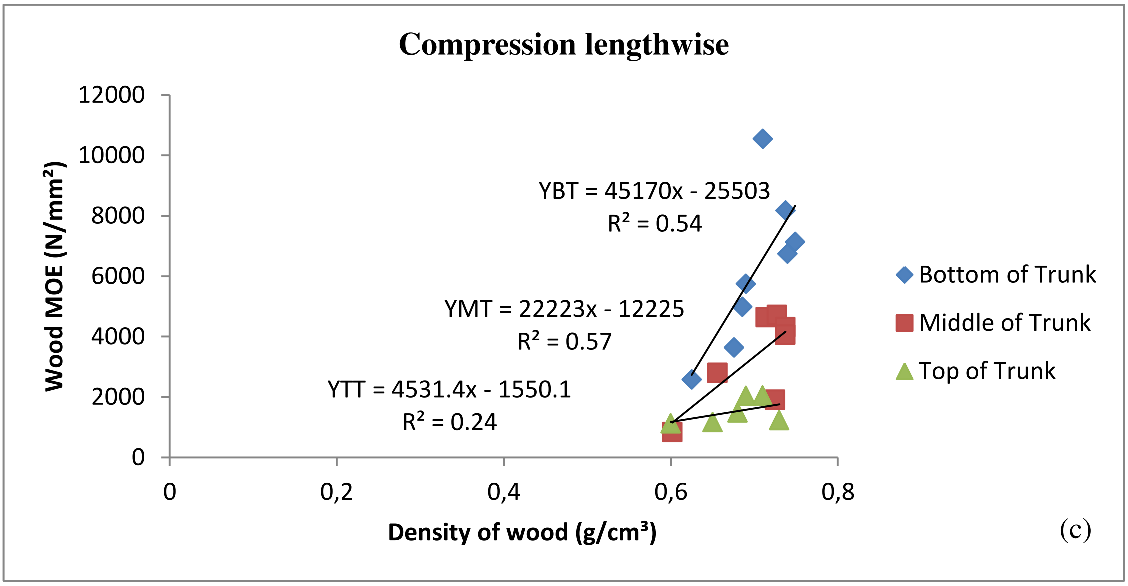
The density of date palm wood, which is closely related to the properties of VBs and ground tissue, does not have a distinct variation between three different zones along the trunk diameter as well as along the trunk height. Figure 71 shows a weak correlation between the wood density and the total area of VBs. The MOR in compression of wood depends positively on the wood density (medium correlation) but very weakly on the total area (percentage) of VBs. Therefore, knowing only the distribution of the total area (percentage of VB from total cross-cut area) of VBs is not enough to model density and mechanical properties of date palm wood. It can be interpreted that, for grading lumber and for developing sawing patterns in sawmill processing, other parameters are also effective; mainly the parenchyma tissue, chemical composition of wood, i.e. lignin, cellulose and hemicellulose and the other anatomical parameters, i.e. proportion of fibers in a vascular bundle, cell wall thickness and microfibrillar angle in the cell wall layers. Considering common grading technologies (i.e determination of density by mass/volume on x,γ-rays or ultrasonic methods), it seems difficult to (a) develop a simple physical-mechanical model and (b) to develop appropriate grading technology in the near future.



(a)



(b)



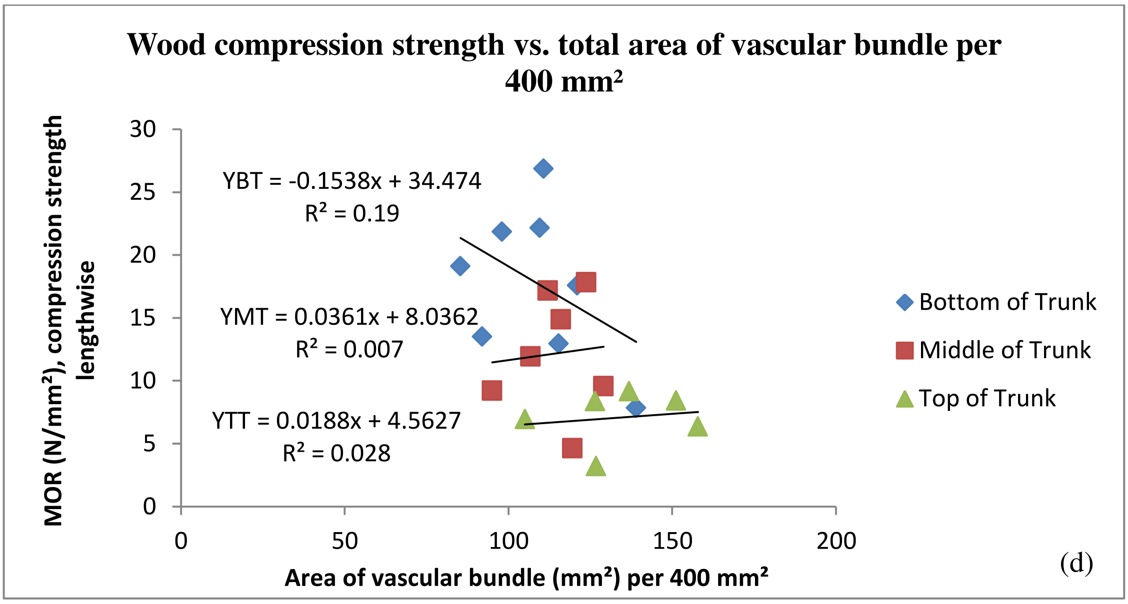
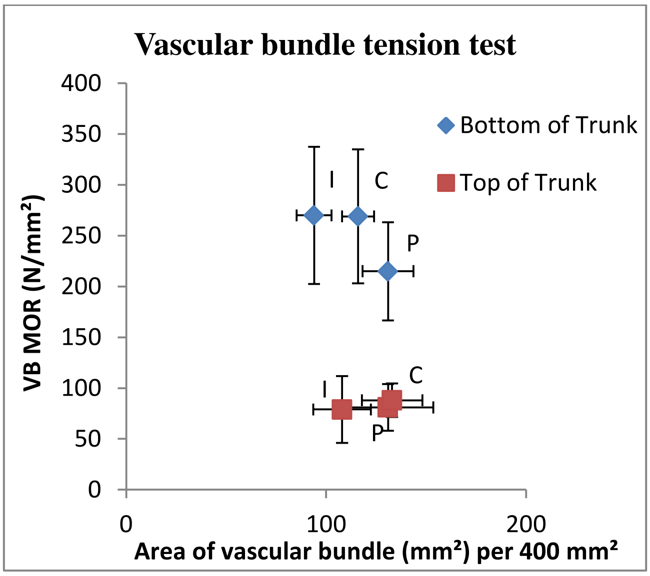
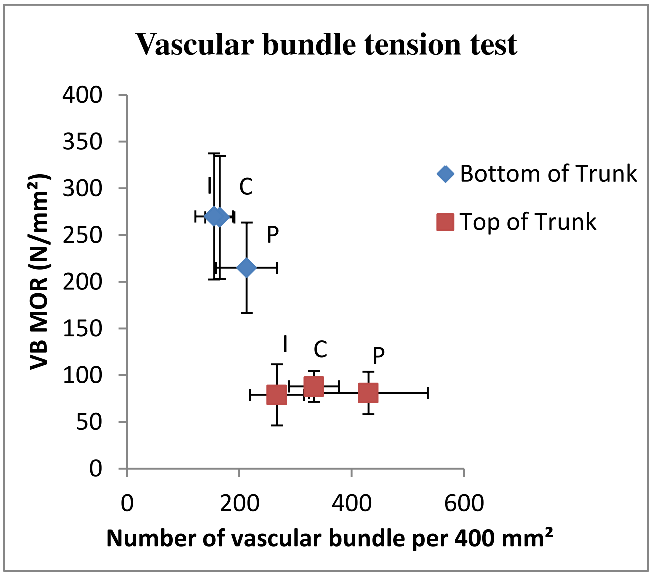
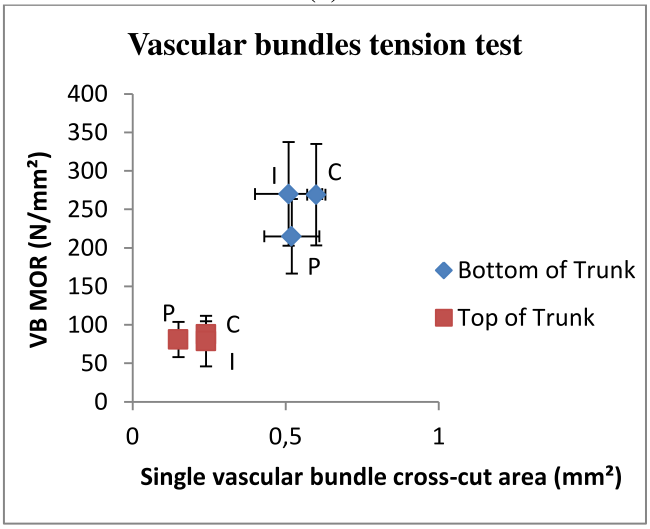


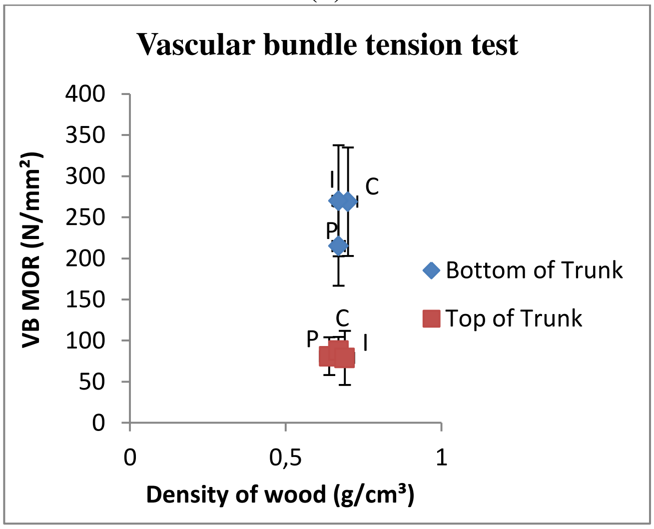
Figure 71. Date palm wood: Relationships between (a) density of date palm wood and total area (percentage) of vascular bundles, wood density and compression strength parallel to grain MOR (b) and MOE (c), (d) compression strength parallel to grain and total area (percentage) of VB

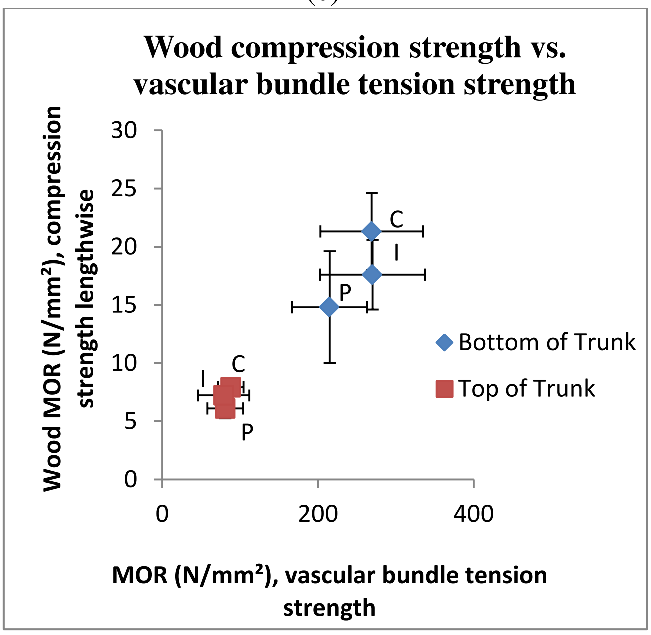
Further statistical analysis was conducted to evaluate the effects of physical and anatomical characteristics on the mechanical properties and the results are shown in Figure 72.

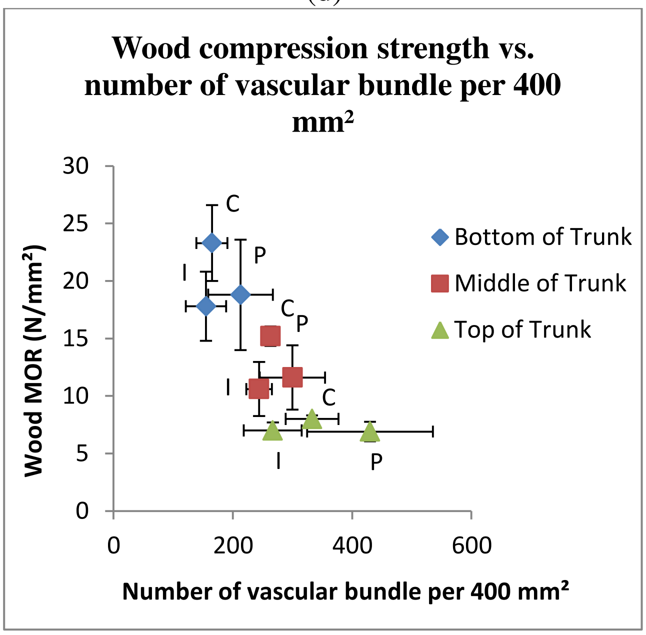

Vascular bundle tension test
VB MOR (N/mm²)
Area of vascular bundle (mm²) per 400 mm²
Bottom of Trunk
Top of Trunk
I
C
P
0
50
100
150
200
250
300
350
400
0
100
200
(a)

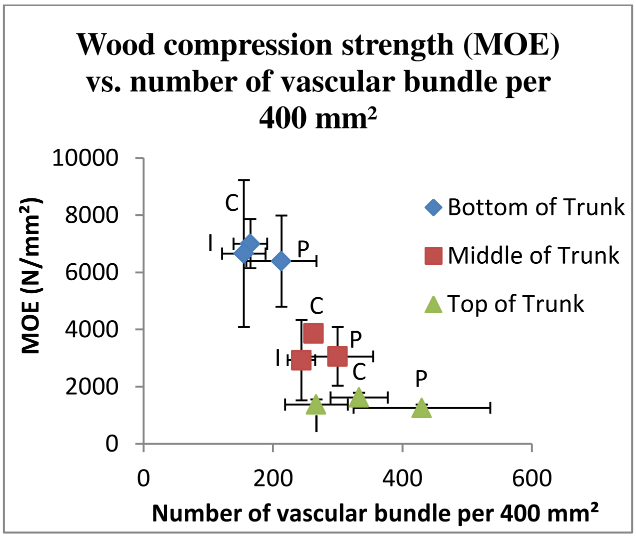

Vascular bundle tension test
VB MOR (N/mm²)
Number of vascular bundle per 400 mm²
Bottom of Trunk
Top of Trunk
I
C
P
0
50
100
150
200
250
300
350
400
0
200
400
600
(b)


Vascular bundles tension test
VB MOR (N/mm²)
Single vascular bundle cross-cut area (mm²)
Bottom of Trunk
Top of Trunk
I
C
P
0
50
100
150
200
250
300
350
400
0
0,5
1
(c)

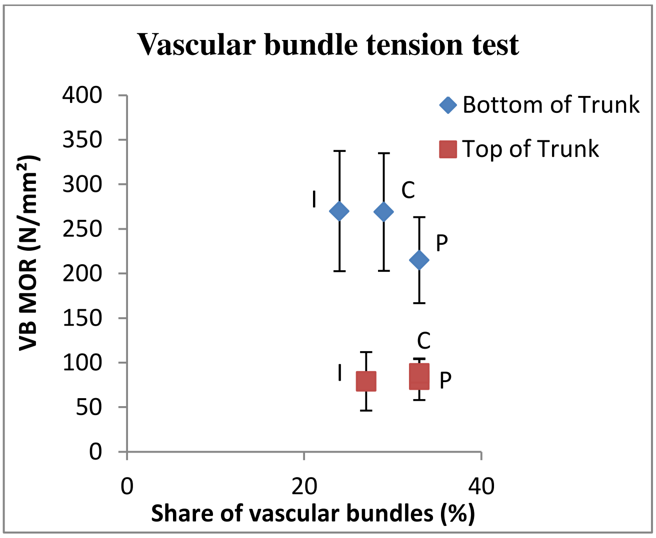

Vascular bundle tension test
VB MOR (N/mm²)
Density of wood (g/cm³)
Bottom of Trunk
Top of Trunk
I
C
P
0
50
100
150
200
250
300
350
400
0
0,5
1
(d)


Wood compression strength vs. vascular bundle tension strength
Wood MOR (N/mm²), compression strength lengthwise
MOR (N/mm²), vascular bundle tension strength
Bottom of Trunk
Top of Trunk
I
C
P
0
5
10
15
20
25
30
0
200
400
(e)


Wood compression strength vs. number of vascular bundle per 400 mm²
Wood MOR (N/mm²)
Number of vascular bundle per 400 mm²
Bottom of Trunk
Middle of Trunk
Top of Trunk
I
C
P
0
5
10
15
20
25
30
0
200
400
600
(f)



(g)



(h)

Figure 72. Date palm wood: Effects of physical and anatomical characteristics on the mechanical properties of wood and single vascular bundles. Relationships: (a) tensile strength VB and total area of VBs, (b) tensile strength VBs and number (frequency) of VBs, (c) tensile strength of VBs and single VB cross area, (d) tensile strength VBs and density of wood, (e) tensile strength VBs and wood compressive strength parallel to grain, wood compressive strength parallel to grain and number (frequency) of VBs; MOR (f), MOE (g), (h) tensile strength VB and share of VBs; P is near "the bark" of the trunk (peripheral), C is in between outer and inner zones (central) and I is near the core of the trunk (inner)

The analysis indicates that properties such as compression parallel to grain at the bottom, in the middle and at the top of trunk positively depend on the wood density and the location in the trunk (R^2= 0.67 bottom of trunk, R^2= 0.55 middle of trunk, R^2= 0.59 top of trunk). The correlation of MOE and MOR in the tension of single VBs with the wood density is weak R^2= 0.047 for the trunk bottom. The relation of MOR and MOR with the location across the trunk diameter is high (R^2= 0.76) but is reverse. This means that in contrary to coconut palm and oil palm, MOR and MOE are lower in the outer zone compared to the inner zone. This follows the small differences in density distribution. Also, the statistical evaluation revealed a weak correlation (R^2= 0.19 between MOR in the tension of single VBs and the density of wood) for the top of trunk. Based on these findings, it can be interpreted that in date palm wood parameters other than density are effective on the mechanical properties of VBs and wood; namely (a) proportion of fibers in a vascular bundle, (b) microfibrillar angle in the cell wall layers in fibers and other cell components in a vascular bundle, (c) number of cell wall layers in fiber cell wall, (d) microfibrillar angle in each cell wall layers in fiber cell wall, (e) composition of lignin, hemicellulose and cellulose in fiber cell wall, or (f) composition of phenolic acids (Fathi et al. 2014). The analysis further indicates that the area of VBs is inversely (R^2= 0.70) correlated with MOR in the tension of single VBs at the bottom of trunk.

Figure 73 shows the calculated relationship between the share of VBs and the MOR of wood in compression lengthwise. In general terms, all relationships are extremely weak. Therefore, it must be concluded that the MOR in compression does not depend on the volume fraction of VB. This conclusion is supported further by the fact that the density of date palm wood also does not depend on the number or the volume fraction of VB (see Figure 74).

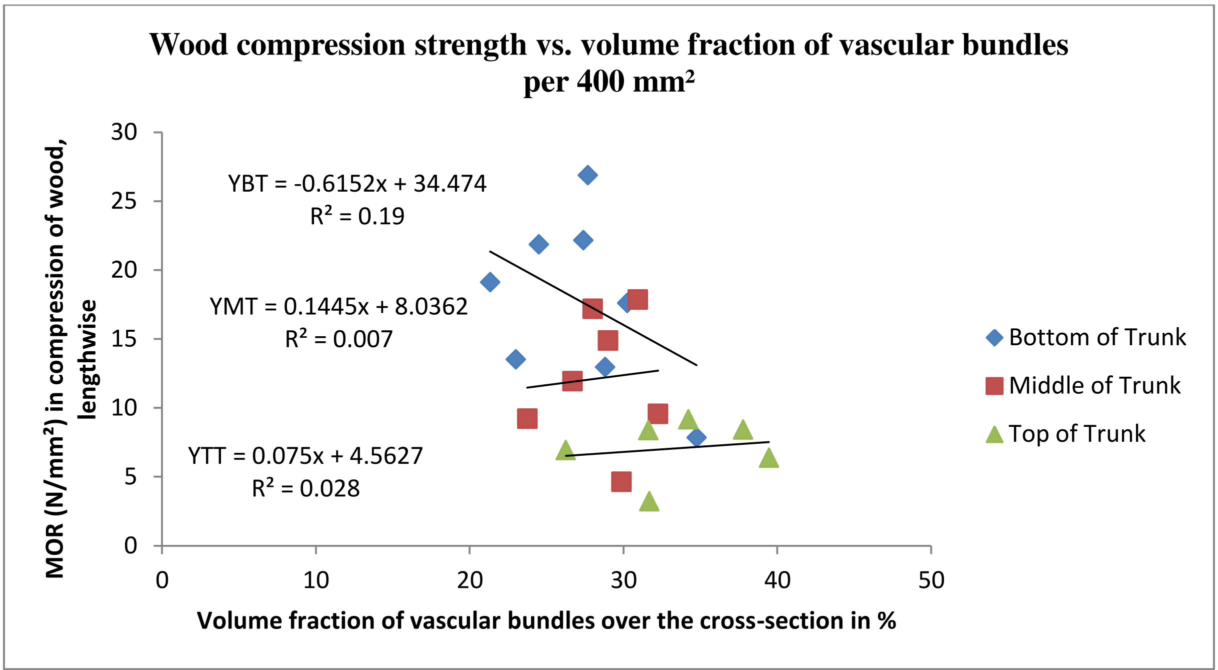


Figure 73. Date palm wood: Relationship between wood compression strength parallel to grain and volume fraction of vascular bundles

In the theory of composite, volume fraction of fiber (vf), which can be calculated from the total area of VBs is a crucial factor in determining the mechanical strength of the composite. But this is not true for date palm wood. According to the regression, the MOR of VBs in compression (calculated with 100% vf) is around 27 MPa at the bottom of trunk, 22 MPa in the middle of trunk and 12MPa at the top of trunk. This implies that in date palm wood, beside of vf, other parameters are also effective on the MOR of VBs in the compression (compare to the findings in chapter 5.5.1.2, oil palm).

Vascular bundle diameter (tangential) is positively correlated with wood compression strength, MOE and tension strength of single VB. This indicates that an increase in tangential diameter of VBs is accompanied by an increment of strength properties.

The results also show that with increasing mechanical properties of single VB, strength properties of date palm wood increase, especially at the top of the trunk.

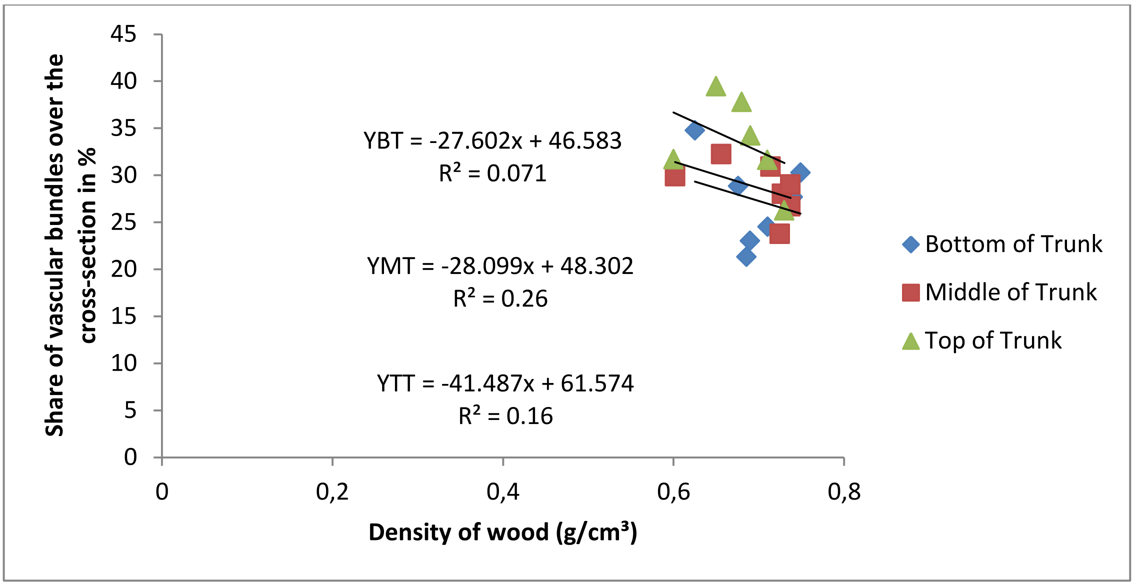
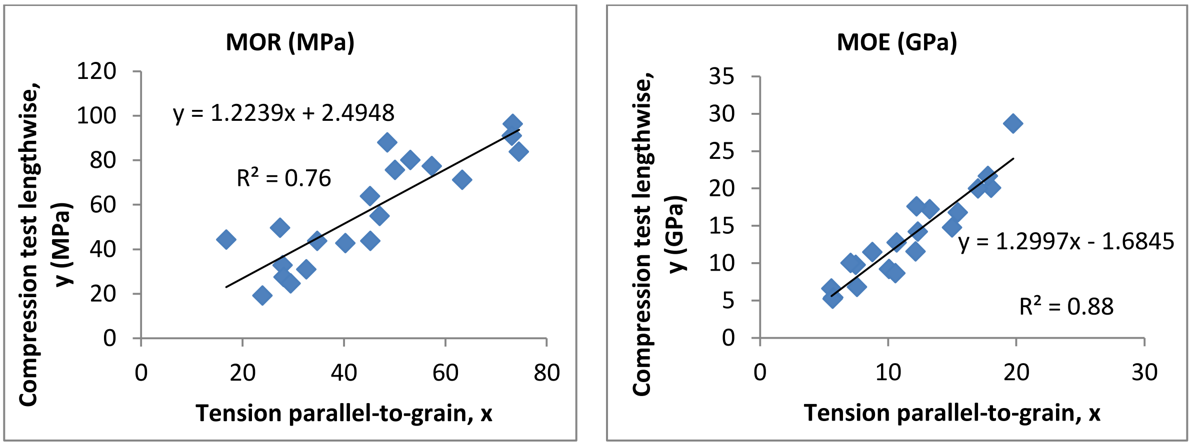


Figure 74. Date palm wood: Relationship between share of vascular bundles over the cross-section and density of wood

5.5.2 Relation of compression parallel to tension parallel and shear parallel to tension perpendicular, coconut wood (Indonesia), bottom of trunk

Figure 75 and 76 show the correlation between some mechanical properties of coconut wood. All correlations are high, which means that strength properties are closely related to each other, similarly as common timber species. Figure 75 show the regression between compression lengthwise and tension parallel-to-grain.



a) (b)

Figure 75. Coconut wood (Indonesia, trunk bottom): Relationship between compression test lengthwise and tension parallel strength.

Figure 76 shows the regression relationships between shear parallel-to-grain and tension perpendicular-to-grain.

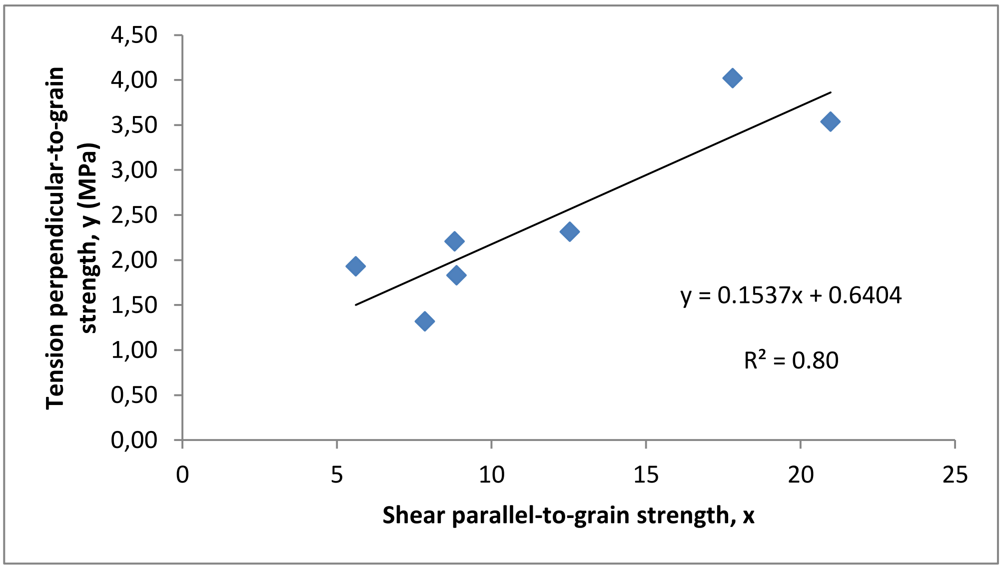


Figure 76. Coconut wood (Indonesia, trunk bottom): Relationship between shear parallel-to-grain and tension perpendicular-to-grain strength

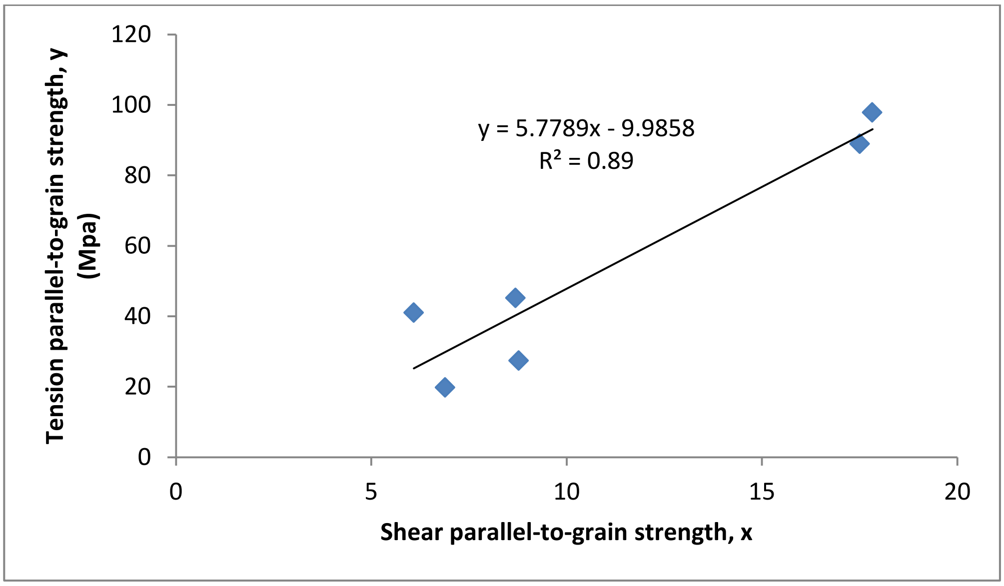


Figure 77. Coconut wood (Indonesia, trunk bottom): Relationship between shear parallel-to-grain and tension parallel-to-grain strength

From these figures, it is clear that relationships among properties are described very well by simple linear models. The highest correlation (R^2= 0.89) is found between the shear parallel-to-grain and the tension perpendicular-to-grain (Figure 77). The second highest correlation (R^2= 0.88) is found between the compression lengthwise (MOE) and the tension parallel (MOE) (Figure 75b). The third highest (R^2= 0.80) is observed between the shear parallel-to-grain and the tension perpendicular-to-grain (Figure 76). Also Figure 76 reveals that the shear strength is more influenced by the density compared to the tension strength perpendicular-to-grain.

Table 47. Summary of linear regressions for properties (Y = mx+b)

Y	X	m	b	R^2
Compression lengthwise	Tension parallel (N/mm²)	1.22	2.495	0.76
MOE compression lengthwise	MOE tension (N/mm²)	1.2997	- 1.6845	0.88
Tension-perp	Shear parallel	0.1537	0.6404	0.80

The compression parallel-to-grain values correlates strongly with the tension parallel-to-grain results while the tension perpendicular-to-grain values correlates strongly with shear parallel-to-grain results. The correlation presented in Table 47 supports these findings.

5.6 Overall discussion

Coconut palms, oil palms and date palms are grown on large areas. The most important producing countries are in Southeast Asia, with much less produced in Central America and in West Africa. In light of the decline in availability of traditional timber within these regions, palm wood offers a viable alternative with unique technical and economical aspects. The total volume of palm trunks from replanted areas is estimated at 100-200 million m³ of wood volume per year. Palm wood is highly variable in physical and mechanical properties. There are many advantages to palm wood: good availability, straight trunk growth, good yield in processing, no anisotropy of the wood and different densities for different uses (coconut and oil palm wood) and sufficient wood properties for most uses low cost raw material. The disadvantages, on the other hand, are the extreme density and property variations and low durability resulting from the wood's structure.

The overall objective of this research was concentrated on the experimental investigation of the anatomical, physical and mechanical properties of wood from trunks of coconut palm (Mexico and Indonesia), oil palm (Thailand) and date palm (Iran).
It was intended to evaluate the relationship between structure, density and mechanical properties of palm wood in order to enable better product design, product properties engineering and processing of palm wood.

Valuable scientific knowledge of the anatomy of coconut, oil and date palm wood was gathered through the microscopic and macroscopic investigations using both light microscopy and scanning electron microscopy. The physical and mechanical properties across and along the trunk were examined through laboratory tests, followed by mathematical and statistical analysis.

This thesis was supplemented by various B. Sc and M. Sc projects (partly using the same material for their experimental research) namely: Tufashi (2013) (Chemical properties and gluing of palm wood), Kurz (2013) (Drying of oil palm timber), Ottenlinger (2014) (Commercialization of oil palm wood), Bockel (2013) (Characterization of block board with oil palm core), Hasemann (2012) (Cross laminated timber from coconut wood), Gurr (2012) (Gluing properties of coconut wood) and Bahmani et al. (2014) (Environmental friendly short-term protection of palm wood against mould and rot fungi).

This PhD-thesis concentrated on basic material research and provided ground for applied research and development projects as mentioned above. More applied research is necessary for commercialization of palm timber i.e. logistics, grading of round wood and lumber, machining and evaluation of design values for timber construction.

5.6.1 Summarized findings

On the basis of the above mentioned experimental investigations, the following conclusions can be made:

(a) The conducted experimental research was focused on the relation between macroscopic anatomical structure and physical-mechanical properties. It was aimed at building a basis for (a) a "tool box for grading palm lumber/timber" and (b) a tool box for "product engineering" to be able to allocate the best suitable material to the various uses.

The main working hypothesis was that by studying the character of the wood tissue, namely the share and structure of vascular bundles (VBs) and parenchyma, it would be possible to develop an information base which could be used for wood characterization and to develop the appropriate grading/engineering need to make best use of palm wood.

(b) The experimental results, analyses and evaluation of the structural and physical-mechanical properties of palm wood show a much higher level of complexity than was assumed and discussed in literature. Although palm wood is a complex composite, little knowledge exists on the fundamental structure and relation to material properties. Only few comprehensive reports are available on how to compare palm wood with traditional timber in the sense of properties, manufacturing technologies, similarities in uses and all seen from an engineering point of view. The structure of palm wood with its ground tissue (parenchyma) and reinforcing elements (VBs) is fascinating and allows room for engineering product design. What is necessary in the future is to develop a mechanical model for the material palm wood. The process towards a "mechanical model/engineering tool box" is quite complex because:

1. The distribution of VBs along the radial and longitudinal direction of the trunk is extremely widespread, but follows certain roles, especially for coconut and oil palm.
2. The size and shape of VBs varies even more compared to the distribution which is not only caused by location within the trunk, but also due to the age (additional cell wall layers) site, growth conditions and other unknown factors.
3. The density and therefore strength properties of VBs varies according to location in the trunk which is additionally heavily influenced by age of the bundles/tree (secondary cell wall layers).

4. The parenchyma structure and density vary as well, but the variation is more unclear for the density distribution and even more the mechanical properties. Especially with parenchyma structure and density, a distinct variation can be observed between palm species. In contrast to coconut or oil palm, the date palm expresses only small variation in wood density within the trunk, which needs more detailed research on the cell formation and (secondary) growth within the trunk and with the age of the palm. For date palms the mechanical properties vary in a wide range with almost no statistical correlation with density. This is contrary to other palms and cannot be explained yet.

5. Apart from these properties variations and partly for unclear reasons, some mechanical properties, their variation and relation to structural parameters, are clear enough to serve as criteria for grading lumber based on density and strength properties.

6. Also tests prove that most mechanical properties are related to each other. Aspects and theory of composite material (matrix and reinforced elements) could lead to a mathematical-mechanical model to describe the mechanical behavior of at least coconut and oil palm wood. One complex example is the relationship between tension strength and shear strength which is much closer for palm wood than compared for example to "normal wood"(dicotyledons). Furthermore, shear properties are much more relevant for "common properties" like tension, compression and bending strength than compared to traditional timber species.

5.6.2 Anatomical characteristics of palm wood (coconut, oil and date)

Based on visual observations, the trunk shape of all three palms at transverse section is normally circular and two parts can be distinguished, e.g. the main part of the trunk ("wood") and the cortex ("bark"). The main part of the trunk (not for date palm) can be divided into three major trunk zones, inner, central and peripheral zone, each representing a density class.

The color of the palm wood (discoloration caused by fungi or bacteria not considered) is dominated by number, size and color (age) of the VBs. Therefore, along the trunk cross-cut area, the peripheral part is darker in color than the inner part. The same appears along the trunk height, the top is generally of lighter color. Only frequently oil palms develop a more dark brown color all along the trunk diameter (predominantly at the base of the trunk) which is accompanied by (much) higher density (up to 1.0g/cm³). The wood expresses an increased number and size of VBs and thicker wall for the parenchyma cells. No explanation for this could be given from the plantation site conditions or the genus of the plant.

Based on microscopic investigation, the wood structure of coconut, oil and date palm is of different structure in comparison with common timber species. VBs are composed of fiber caps (containing fibers with a wide range of sizes and wall thicknesses), vessels (thin walled) and parenchyma cells (thin walled). The number and size of the vessels differ according to location within the trunk (one or two large vessels near the trunk periphery, two or three vessels, often smaller, near the trunk center). Also, fiber caps size and fiber wall thickness varies according to the location in the trunk. The large vessels are considered the main transport component for water and nutrients. A typical vascular bundle consists of vascular tissue and a fibrous sheath. The vascular tissue is divided into (i) xylem, composed of solitary metaxylem and protoxylem elements with xylem parenchyma, and (ii) phloem, found in two strands located on the lateral sides of the metaxylem associated with the fibrous sheath.

The VBs are embedded in parenchymatous ground tissue; therefore this wood material is not comparable to the wood produced from dicotyledon (angiosperms and gymnosperms) species which is normally developed from the cambium. This finding is in agreement with Parthasarathy and Klotz (1976), who investigated the anatomical aspects of some monocotyledon species.

The number of VBs decreases significantly toward the central zone of the trunk. Based on these findings, it is recommended to use the coconut, oil and date palm wood from different locations inside the trunk separately.

According to the results of Gibson (2012), the concentration of VBs as well as the concentration of fibers within the bundles is greater at 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. Higher magnification scanning electron micrographs of coconut palm wood indicated that the thicker cell walls have additional secondary layers, which agrees with findings of Kuo-Huang et al. (2004). These observations show the necessity of more research on the influence of tree age on the secondary growth. It is obvious that secondary thickening of cell walls takes place primarily and earlier in the lower, peripheral zone of the trunk. From this fact the distribution of density and strength properties within the trunk is obvious. The questions (under practical aspects of wood utilization) are:

(a) How is the development of secondary growth (wall thickening) influenced by the age of the palm (coconut palms are felled after 50-60 years and show general higher densities compared to oil palms which are felled after 25 years)?

(b) Will the palm wood properties of oil palms investigated at an age above 25 years show a further increase in density and strengths?

(c) Will the variations in density/strength across/along the oil palm trunk become smaller or remain wide at higher ages?

Along the cross section of coconut and oil palm, all anatomical structures near the outer zone ("bark") are significantly different from those near the inner zone of the trunk. The anatomical features quantity of VBs, VB cross-cut area, VB diameter and area of VB increases linearly in transverse direction, from the inner zone to the outer zone.

The wood zones over the cross-cut area and along the length of the trunk were determined due to the high variation of properties such as anatomical, density, and mechanical properties. The different density and properties cause many difficulties in wood manufacturing. Therefore, it is necessary to improve the homogeneity of lumber produced from palm trunks in order to ensure a product which is suitable for manufacturing from both a technical and economic perspective. These wood zones were defined on the basis of VBs distribution and population over the transverse section. The VB population was defined in the experiments by determining the number of VBs per 400 mm^2 of wood area using Cell-F image-software.

Based on the results obtained, it can be stated that the distribution of VBs increased from the central zone of the trunk towards the bark. Three different wood zones were defined, i.e. inner zone (IZ), central zone (CZ) and peripheral zone (PZ). The average number of VBs at the inner, central and peripheral zones were approx. 109; 180 and 288 in coconut wood;101; 121 and 201 in oil palm trees and 155; 165 and 213 in date palm trees, respectively.

5.6.3 Density of palm wood

An important factor in determining the mechanical properties of coconut and oil palm wood is the density of wood as it increases from the center of the trunk towards the "bark". In date palm, however, there is no significant difference across the trunk. On the other hand, it is proved that at the bottom of the trunk, the density of coconut and oil palm wood is closely related to the distribution of VBs (R^2= 0.995/R^2= 0.97), but in the date palm wood, there is no relationship found between density and the distribution of VBs (R^2= 0.03). More in detail the density of Mexican coconut wood shows a significant increase from the inner to the outer part. Whereas Indonesian Coconut "wood" shows a wider variation of densities across the trunk. Because of it’s in homogeneity, based on own practical experience and literature findings with coconut wood, three groups of density suggested.

HD: high density timber (hard, over 800 kg/m^3),

MD: medium density timber (medium, 600-800 kg/m^3),

LD: low density timber (soft, below 600 kg/m^3).

The density of coconut palm wood at the very outer peripheral zone was higher (1.11 g/cm^3) compared to the other two zones.

According to the statistical analysis, it can be stated that the coconut palm wood density at transverse section was constantly increased from inner to peripheral zone and constantly decreased from the bottom to the top of the trunk. Due to the utilization of coconut palm wood, it is necessary to use this material separately based on their wood zoning.

The density of oil palm wood from the inner zone is 0.36 g/cm^3, on average, ranging from 0.30 to 0.46, and for the central zone on 0.41 g/cm^3, on average, ranging from 0.38 to 0.45. The density at the peripheral zone was higher compared to the other two zones and has an average of 0.56 g/cm^3, ranging from 0.51 to 0.59. The pattern of density distribution in oil palm trunks follows the patterns in coconuts palms but some 0.1 to 0.2 g/cm^3 lower in the inner zone and 0.25 to 0.35 g/cm^3 lower in the outer zone. Other research has found even lower densities in the inner zone (Erwinsyah 2008). For oil palm the density range across the trunk is higher than along the trunk.

In oil palm the VBs and their fiber cells are laminated and sclerotized and their volume fraction increases higher than the parenchymatous ground tissue from the IZ towards the PZ and from the top to the bottom of the trunk. The higher volume fraction of VB resulted in higher density. Furthermore, the fiber cells are laminated and sclerotized with age and the cell wall thickness of the fibers is increased, the zone of highest density is located then in the lower outer zone of the palm stem (see above).

Results from previous research on the increasing density from IZ to PZ of the stem in the cross section were proved (Lim and Khoo 1986; Erwinsyah 2008), however the decrease in density with increasing height of the trunk was lower from across the trunk.

Due to the utilization of oil palm wood, it is necessary to use this material separately based on wood zoning. The date palm stem shows only small variation in density from the inner to the outer zone of the trunk and also from bottom to the top of the trunk. No literature was found to confirm these findings for date palm.

5.6.4 Mechanical properties of palm wood (coconut, oil and date palms)

Several mechanical properties of coconut palm wood were investigated with regard to the location wood of the samples in the trunk. Tension properties (MOR and MOE) of single VB, shear strength parallel to grain (only for coconut wood), compression strength parallel to grain, tension parallel and perpendicular to grain (only for coconut wood) were tested.

Further statistical analysis was conducted to study the effect of wood density on shear parallel-to-grain, compression test lengthwise, tension perpendicular-to-grain and tension parallel to grain.

In coconut and oil palm wood, density and MOE/MOR of single VB increase linearly from the inner part to the outer part and decrease from the bottom to the top of the trunk. In conclusion, the VBs vary in strength and stiffness.

In date palm wood the VBs show only small density variation with regard to the MOE and MOR of VB.

According to the experimental results and statistical analysis, it can be stated that the coconut wood and oil palm wood in the peripheral zone show higher mechanical strength in comparison to the wood from the inner zone. Along the cross section, the density and amount of VBs near the outer zone are higher than those at or closer to the inner zone. Therefore, the strength is also higher near the outer zone, resulting from an increase in density and the amount of VBs. These results are similar to findings of previous research (Frühwald et al. 1992).

Date palm wood in the central zone shows a higher compression value parallel-to-grain in comparison to wood in the inner and peripheral zone.

For coconut wood from Indonesia, it could be demonstrated that:

- All properties tested are increased with increased wood density.
- Shear strength is closely related to density of the parenchyma.
- Density (espec. parenchyma density) has a significant impact on perpendicular tensile strength. The density influence is less pronounced that those on tension strength parallel-to-grain.
- Tension parallel-to-grain strength and tension perpendicular-to-grain are very sensitive to changes in density. The influence on tension and compression parallel to grain is influenced when loading is not exactly parallel to VB-direction (which is rarely the case as VB run not parallel to the stem axis). Also bending behaviour is very much influenced by the low shear properties and tension-perpendicular to grain properties as easily shear forces and forces across the bending axis can cause failures.
- The MOE for both compression and tension parallel-to-grain is quite sensitive to density, therefore, classification of timber according to trunk zones is very important for strength and stress grading for technically and economically best use of palm timber.

- The compression parallel-to-grain values are strongly correlated with tension parallel-to-grain results and also the tension perpendicular-to-grain values are strongly correlated with shear parallel-to-grain results. After the test evaluation this seems quite obvious as the same structural components (VBs and parenchyma) are relevant for the respective properties.
- Strength values in compression parallel to grain, tension parallel to grain, tension perpendicular to grain and shear parallel to grain obtained from testing are comparably high. The results obtained by Sulc (1983) and Palomar (1986) confirm the results presented in this study.

Based on the results, further research and promotion, coconut wood and oil palm wood will become an extremely valuable commodity. Increased utilization of coconut and oil palm wood may, therefore, help conserve the tropical rain forest species which currently continue to make up the bulk of local timber markets.

6. Research outlook

Based on a literature survey and own experimental research, the following recommendations for further research can be given:

6.1 Recommendations for basic (scientific) research

1. Much research has been done on the coconut wood and oil palm wood with focus on mechanical features of the trunk, whereas the date palm stem wood has never been thoroughly studied as an alternative to commercial timber.

- Study mechanical properties of date palm wood, namely shear strength, bending strength, tension perpendicular and parallel to grain strength, in order to characterize date palm wood for product utilization.
- Study the density of date palm wood and also tensile strength of single VB which showed no significant difference in transverse direction of the trunk, but the compression strength is higher in the central zone compared to the peripheral zone. Investigate what exactly is causing the higher compression strength in the central zone of the trunk.
- Test number, size, density and strength (also secondary growth) of date palm VB.

2. Little information is available on the content and distribution of main chemical constitutions of palm wood in general (cellulose, hemicelluloses and lignin) and their relation to mechanical properties.

- Relationship between lignin distribution and mechanical property of vascular bundle in oil and date palm wood should be investigated.

3. As structure of VB and structure of wood (composition of VB and parenchyma) has a major influence on all physical-mechanical properties research is recommended on:

- Structure and anatomical properties such as (a) proportion of fibers in a VB, (b) microfibrilar angle in the cell wall layers in fibers and other cell components in a vascular bundle, (c) number of cell wall layers in fiber cell wall, (d) microfibrilar angle in each cell wall layer in fiber cells, (e) composition of lignin, hemicellulose and cellulose in fiber cell wall and (f) composition of phenolic acids should be investigated in coconut, oil and date palm wood and the effect of these factor on the tensile strength of single vascular bundle should be evaluated.

4. During experimental tests it was observed that fungi and bacteria growth is fast due to high sugar and starch content. Due to low parenchyma density (thin cell walls) drying of the wood

is difficult and frequently defects (cell collapse, cracks) occur. It is recommended to perform research on

- the treatment of the date palm (Phoenix dactylifera) stem with chemicals has never been investigated before,
- drying (air drying and kiln drying) of palm wood should be evaluated for effectiveness (time, energy, quality and costs),
- more research on the efficient methods for preventing the rapid fungal decay of the fresh felled stems is required (harvesting and transport/processing logistics).

5. In order to improve the coconut, oil and date palm wood processing and utilization, at least two important factors should be taken into consideration: wood zoning across and along trunk height.

- Wood zoning through appropriate grading is a very important factor in order to reduce the heterogeneity of wood properties. Criteria for grading are density (dry, wet, round wood and lumber) and strength (dry, lumber). Well-established methods for the grading of lumber are:

(1) density calculation (mean value) from mass and volume,
(2) density measurement with γ- or X-rays (or similar),
(3) strength/elasticity grading by deflection, ultrasonic or eigenfrequency,
(4) scanning technologies (normally used for knots, cracks, fiber angle; not preferably required for palm timber),
(5) determination of VBS.

Therefore, according to the findings in this study, it is recommended that coconut, oil and date palm wood be studied separately based on the wood zoning (inner, central and peripheral zone) to improve the homogeneity of the produced lumber or timber.

6.2 Applied research

Due to the high availability of the coconut, oil (and date) palm wood, this material has a high potential for substituting wood from natural forests. Yet the wood quality of palm wood presents several disadvantages:

(a) Regarding biological properties, the content of carbohydrates in the sap of fresh wood causes the fast growth of mould and wood deterioration fungi on fresh wood. This calls for special logistical and processing measures. The problem no longer exists once the timber is dried.

(b) High variability in anatomical and physical properties along the trunk height and depth as well as mechanical properties requires a strong emphasis on grading and optimal allocation of the different grades to the end use.

(c) A potential problem exists with the ash and silicate content in the wood. It is definitely higher than that of common timbers and can cause heavy abrasive wear to the cutting tools and also lead to higher costs (Tufashi 2013). At least satellite tipped, better tungsten carbide tipped or diamond tipped tools should be tested and used.

But, palm wood also has many advantages, besides being widely abundant throughout the year; the palms have relatively straight trunks without branches and are also easily accessible for harvesting.

Therefore, the coconut, oil and date palm wood have a very good prospect for furniture, panel based products and the structural material purposes as well.

(d) The use of palm timber requires more research and development efforts. For that some general recommendations are given:

d_1: Building purposes:

For load bearing structures HD/MD coconut wood has been proven suitable, the manufacturing of glued elements (gluelam and cross laminated timber) causes no problems (Frühwald et al. 1992). High density wood from oil palm and generally date palm has potential for medium and lower loads. Non-load bearing uses like roof, wall and floor elements are possible with MD (coconut and oil palm) and preferably LD qualities (coconut palm). Further research is needed on: grading according to density and strength, development of load- design-factors, managing split, shear strength and optimal gluing.

d_2: Furniture and interior decoration:

All density classes from coconut, HD and MD from oil palm and generally date palm seen suitable for furniture, non-load bearing structure and interior decoration. Profiled boards, one or three layer glued solid timber elements show good quality. LD from oil palm as core layer in blockboards (overall density incl. MDF face is below 350 kg/m³) is already on the market. Further research is needed on: grading according to mechanical properties and color, surface treatment, gluing (esp. light timber) and solid wood connection.

d_3: Wood based panels:

Oil palm fronds and empty fruit bunches are already used for MDF; experts believe that wood with a density below 0.7-0.8 g/cm³ is suitable for MDF and particle board. Initial research on OSB from palm wood showed promising results (Akrami and Frühwald 2014). More studies are necessary to produce veneer and plywood (mixture of different densities), wood gluing, fiber and chip production/processing for boards, compression behavior of fiber and particle mats, board properties, material and overall production costs.

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8. Publications

Publication 1

Leila Fathi and Arno Frühwald. 2014.

The role of Vascular bundleson the mechanical properties of Coconut palm wood. Wood Material Science & Engineering. Published on Taylor & Francis Online 24 February 2014, DOI: 10.1080/17480272.2014.887774.

Publication 2

Leila Fathi, Arno Frühwald and Gerald Koch. 2014.

Distribution of lignin in vascular bundles of Coconut wood (Cocos nucifera) by cellular UV-spectroscopy and relationship between lignification and tensile strength in single vascular bundles. Holzforschung (HOLZ). Published on Holzforschung, ISSN (Online) 1437-434X, ISSN (Print) 0018-3830, DOI: 10.1515/hf-2013-0213, April 2014.

Publication 3

Mohsen Bahmani, Olaf Schmidt, **Leila Fathi** and Arno Frühwald. 2014.

Environmental-friendly short-term protection of palm wood against mould and rot fungi.

Paper submitted for Wood Material Science & Engineering, 8. July 2014.

Publication 4

Leila Fathi, Antonio Silva Guzmán, Raul Rodriguez and Arno Frühwald. 2013.

Structure and mechanical properties and potential use of coconut palm wood from Mexico. Proceedings of the 65th International Convention of Forest Products Society, June 2013, Austin, Texas, USA.

Publication 5

Leila Fathi and Arno Frühwald. 2013.

Relationship between structure and mechanical properties of coconut wood (Cocos nucifera).

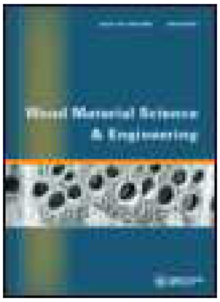
Extended Abstract for the 8th Pacific Regional Wood Anatomy Conference & Annual Meeting of International Academy of Wood Science, October 2013, Nanjing, P.R.China.

Publication 6

Leila Fathi, Katja Frühwald and Arno Frühwald. 2014.

The potential use of timber from palm trees for building purposes.

Proceedings of the World Conference on Timber Engineering 2014, August 2014, Quebec, Canada.



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The role of vascular bundles on the mechanical properties of coconut palm wood

Leila Fathi[a] & Arno Frühwald[a]

[a] Department of Wood Science, University of Hamburg, Hamburg, Germany
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ORIGINAL ARTICLE

The role of vascular bundles on the mechanical properties of coconut palm wood

LEILA FATHI & ARNO FRÜHWALD

Department of Wood Science, University of Hamburg, Hamburg, Germany

Abstract

This study examines certain physical, mechanical, and anatomical characteristics of coconut palm wood. The results show a correlation between the anatomical characteristics and density as well as lengthwise compression. All properties (density, frequency of vascular bundles (VBs), and mechanical properties) increase with the transverse distance from the center of the trunk. The study also tests VBs from different radial sections of the coconut palm tree (Cocos nucifera) for diameter, ultimate tensile strength, and modulus of elasticity. The influence of the VBs on the overall properties of the wood is discussed.

Keywords: *Anatomical structure, coconut wood, physical and mechanical properties, vascular bundles*

Introduction

The coconut palm, *Cocos nucifera*, grows mainly in Southeast Asia and Central America. The total area planted with coconut palms is close to 12 million ha, of which more than 90% grows in Asia. Major coconut wood producers are Indonesia, the Philippines, and India (Asian and Pasific Coconut Community 1998).

Throughout the coconut-producing regions of the world, there is an increasing interest in the utilization of wood from overmature coconut trees (Alston 1976). The performance of coconut wood in industrial uses, construction, and housing is closely related to its physical/mechanical properties and anatomical characteristics. The physical properties of coconut wood depend on the density, moisture content, and shrinkage. Density, for example, helps to determine the physical and mechanical properties and characterize different kinds of wood and woody materials for their intended use (Mitchell 1964, Gurfinkel 1973). It is often observed that the trunk of a coconut palm has a very high variability of dry density, ranging from >1.0 g/cm^3 (lower, peripheral part of the trunk) through 0.4–0.6 (inner part of the trunk) to < 0.35 g/cm^3) (upper, inner part of the trunk). During processing, this variability necessitates a specific sawing pattern for each individual trunk in order to produce boards with low-density variation (Frühwald et al. 1992). The main reason for density variation, resulting in variable mechanical properties, is seen in (1) the number and distribution of vascular bundles (VBs), (2) the dimension (diameter) as well as thickness of the cell walls of the bundles, and (3) the cell wall thickness of the parenchyma as ground tissue of the wood. The density of wood and the concentration of VBs per unit area are important properties for visual and mechanical grading procedures (Sulc 1979). This study examined several physical, mechanical, and anatomical properties of coconut wood at four sections along the radius of the trunk. The interrelationships of physical and mechanical properties in relation to the anatomical characteristics were studied.

Materials and methods

One disk at a trunk height of 2 m above the base of an approximately 40-year-old coconut tree (*Cocos nucifera*) was obtained from a plantation in Jalisco, Mexico (wood from *C. nucifera* grown in Mexico has properties similar to wood grown in Asia). The disk

Correspondence: L. Fathi, Department of Wood Science, University of Hamburg, Leuschnerstraße 91 C, Hamburg 21031, Germany. Tel: 0049 40 73962 608. Fax: 0049 40 73962 699. E-mail: leilafth@yahoo.com

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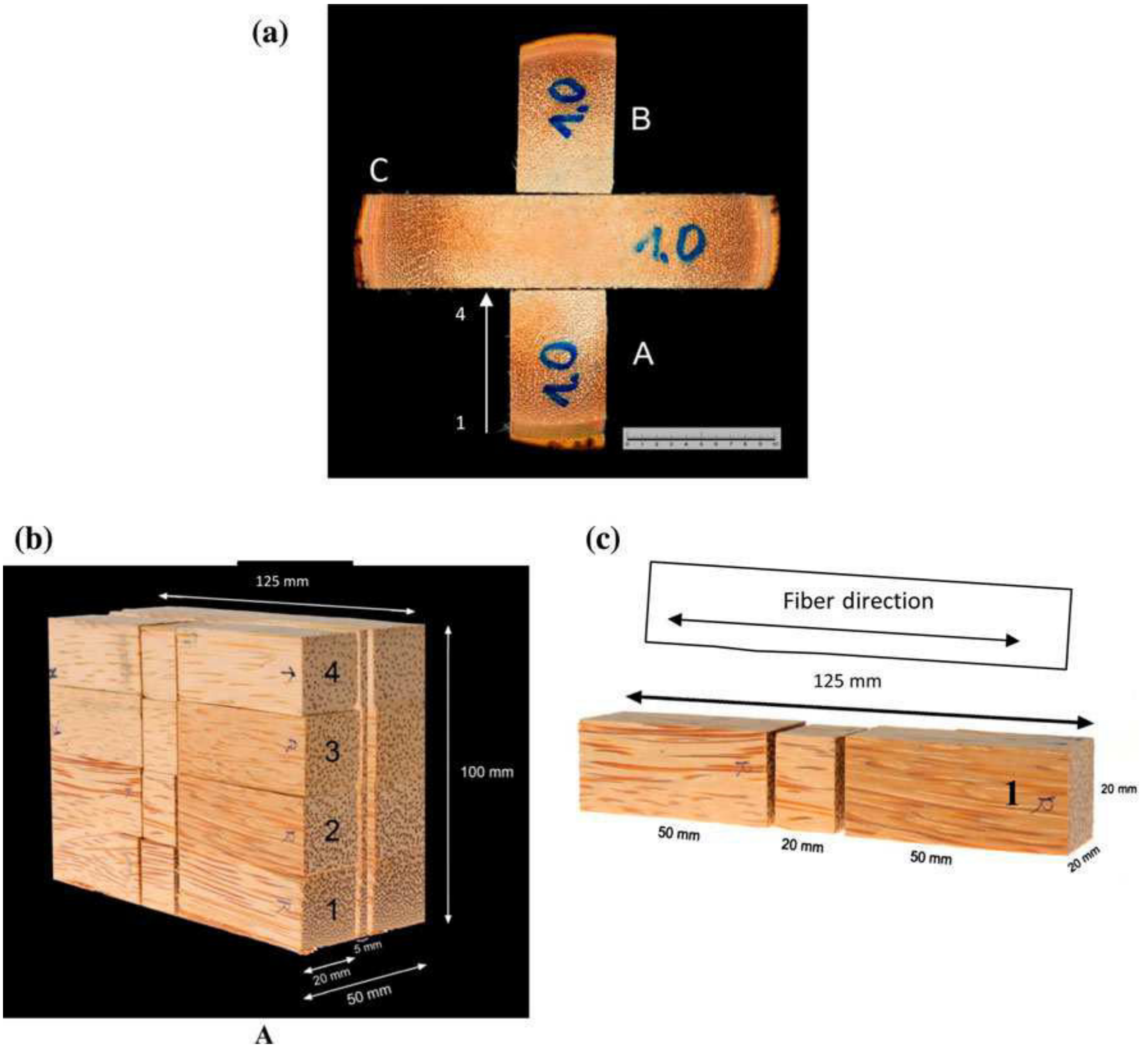

Figure 1. (a) Coconut trunk disk cut into three sections (A, B, C), (b) cutting pattern of section A and (c) Cutting pattern of parts 1–4 from section A.

was 30 cm in diameter and 14 cm thick, parallel to the grain.

The disk was cut into three sections as shown in Figure 1(a).

The sections A and B in Figure 1(a) were precut into four subsections 1, 2, 3, and 4 of each 25 mm (tangential) × 100 mm (radial) × 130 mm (longitudinal) and after drying, into pieces of 125 mm in length, 20 mm in width, and 20 mm in thickness. The 125-mm pieces were cut into three test specimens as shown in Figure 1(c).

The center part with 125 mm in length, 100 mm in width, and 5 mm in thickness (Figure 1(b)) was used to extract VBs, and the remaining part was stored in the deep-freezer.

As shown in Figure 1(c), the bigger parts (50 × 20 × 20 mm^3) were used for compression test lengthwise, and the center part (20 × 20 × 20 mm^3) was used for anatomical and physical tests.

The compression properties, modulus of elasticity (MOE) and modulus of rupture (MOR), were tested according to DIN 52185 (Figure 2(a)). The specimen dimensions were measured with a caliper to an accuracy of 0.01 mm. A total of 16 specimens were tested as shown in Figure 2(b).

Special care was taken in preparing the compression parallel to grain test specimens to ensure that the end grain surfaces were parallel to each other and at right angles to the longitudinal axis.

The anatomical characteristics were measured by light microscopy. The cross-section of specimens used for anatomical characteristics was (20 × 20 × 20 mm^3) (Figure 3(a) and 3(b)). A light microscope equipped with a digital camera (Olympus, SZ H10), was used to take images of the cross-section. The anatomical parameters (number, cross-cut area of single VB, and diameter of VB) of VBs are determined using Cell-F image-software. Since the

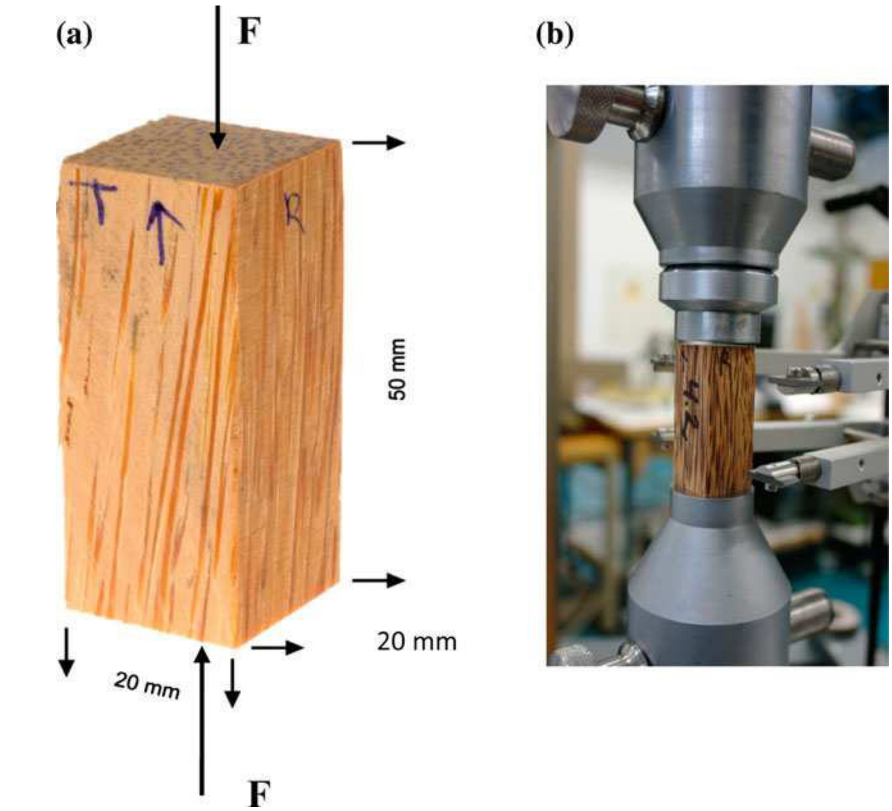

Figure 2. (a) Compression parallel to grain specimen dimensions, (b) compression parallel to grain apparatus.

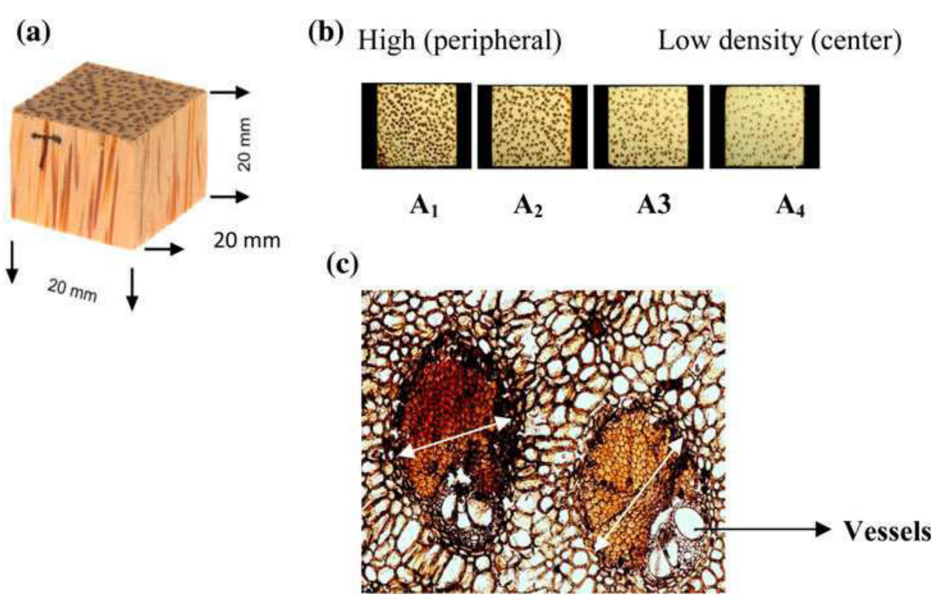

Figure 3. (a) Sample for density and anatomical tests, (b) cross-section of coconut palm stem and (c) VBs.

cross-section of VBs is not perfectly circular, the VB diameter was measured as shown in Figure 3(c).

For tensile strength of single VB, they were extracted from the wood. A single VB was carefully picked out under a stereo microscope. Once the surrounding matrix was completely removed, the VB was kept straight throughout the seasoning process (Figure 4).

For tensile tests, VBs were cut to a length of 50 mm. Two sample holders of aluminum were used, and the specimen was glued into the two sample holders as shown in Figure 5. A two-component glue of epoxy

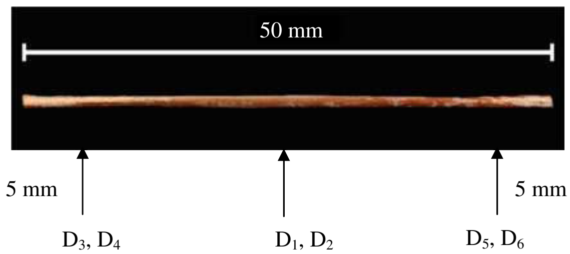

Figure 4. The coconut VB (D_1 … D_6 = diameter measurement points).

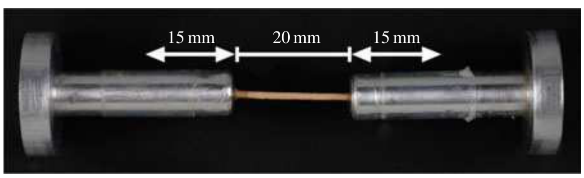

Figure 5. Metal sample holder set-ups for tensile testing of single VB.

type was used. The sample holders were clamped into a Zwick/Roell universal testing machine equipped with a high-resolution 50-kN load cell. The VB diameter was measured with a digital caliper at a precision of 0.01 mm at three points along the length and with two diameters. These six measurements were used to calculate the cross-cut section and volume. The VBs (fiber caps) are not circular in cross-section. But the measuring error for the cross-cut section is less than 3%, and for the volume between 3 and 5%. A minimum of 20 samples was tested in each sample group. All measurements were made at 65% (r.h.) and 20°C (which leads to an equilibrium moisture content of ~12%). Strain measurements were performed with strain electronic measurement devices over a length of 10 mm. The typical tensile stress-strain curves of single VB are presented in Figure 6.

Results and discussion

Tension properties of VBs

To investigate the variation of the mechanical properties of VBs in the radial direction, more than 20 VBs in each subsection (Figure 1b) were separated and tested. The average strength and average Young's modulus of VBs from each subsection were measured. The test results for tension properties of single VB (MOE and MOR) are given in Table I. Figure 7 shows the relationship of MOE and MOR, respectively, and relative radius from the center. From these figures, it becomes clear that relationships are described very well by simple linear models. The VBs near "the bark" of the trunk show

Table I. Average mechanical properties of VBs.

VBs location in subsections[a]	Tensile strength (MPa)	Standard deviation (MPa)	MOE (MPa)	Standard deviation (MPa)
A_1	344	60.7	25144	4545
A_2	341	56.8	23669	3135
A_3	327	71.7	20641	3608
A_4	228	69.5	17636	5465

[a]Values shown for subsections are based on 20 VBs; A_1 is near "the bark" of the trunk, A_2 and A_3 are in between outer and inner layers, and A_4 is near the core of the trunk.

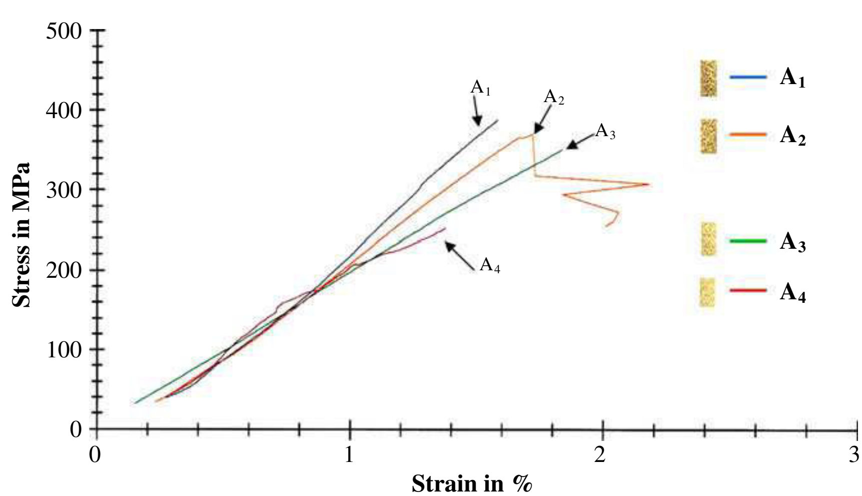

Figure 6. Typical tensile stress-strain curves of single VB (A_1 is near "the bark" of the trunk, A_2 and A_3 are in between outer and inner layers, and A_4 is near the core of the trunk).

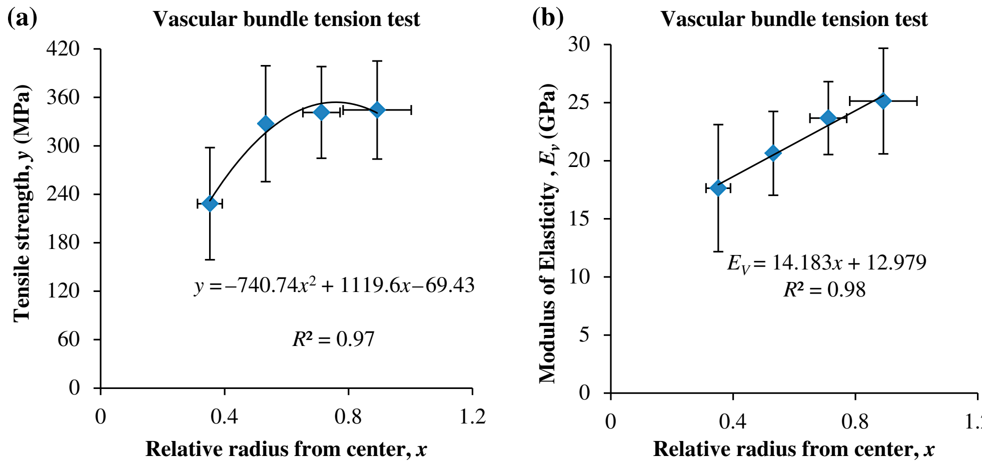

Figure 7. Variation in the mechanical properties of VBs along the radial direction (a) tensile strength and (b) MOE.

higher properties than those near the trunk core (Figure 7(a)), and the strength variation for all the four subsections can be expressed by the following formula:

$$y = Ax^2 + Bx + C, \quad (1)$$

Where y is the tensile strength of VB; x is relative radius from center, thus $X = 0$ corresponds to the inner surface and $X = 1$ to the outer surface. The constants A, B, and C depend on the location, which are A = −740.7, B = 1119.6, and C = −69.4.

The VBs near "the bark" of the trunk are stiffer than those near the trunk core (Figure 7(b)). The correlation between the Young's modulus and relative radius from center is linearly increased as also was observed in the tensile strength, and it can be expressed by the following:

$$E_v = ax + b, \quad (2)$$

Where E_v is the Young's modulus of VB, and the constants a and b are a = 14.2, b = 12.98.

Table II. Density of wood according to distribution in radial direction.

Samples in subsection[a]	Average density (kg/m^3) at mc = 12%	Standard deviation (kg/m^3)
A_1	820	0.02
A_2	710	0.04
A_3	530	0.05
A_4	410	0.04

[a]Values shown are averages of six samples; A_1 is near "the bark" of the trunk, A_2 and A_3 are in between outer and inner layers, and A_4 is near the core of the trunk.

Density characteristics of VBs

The average density of coconut tree is shown in Table II. The density was observed to be in the range of 410 – 820 kg/m^3 with the highest mean value at the outer portion (820 kg/m^3). This involves thicker fiber walls and an increasing concentration of VBs in the outer portion of the trunk.

Anatomical properties

The anatomical properties of the coconut wood investigated are presented in Table III and Figure 8.

Table III. Number and dimension of VBs.

Samples in subsections[a]	Number of VBs per 400 mm^2	Single VB cross-cut area (mm^2) (average)	Single VB diameter (μm) (average)	Total area of VBs (mm^2) per 400 mm^2
A_1	288 (25.5)	0.50 (0.12)[b]	878 (148.4)[b]	174 (26.87)
A_2	197 (11.3)	0.55 (0.10)[b]	978 (124.6)[b]	148 (6.36)
A_3	162 (6.4)	0.39 (0.12)[b]	855 (124.3)[b]	93 (1.41)
A_4	109 (9.2)	0.30 (0.05)[b]	761 (94.2)[b]	50 (4.24)

[a]Values shown are averages of two samples with each 400 mm^2 square; [b]Values shown are averages of 60 VBs; Values shown in parentheses are standard deviation; A_1 is near "the bark" of the trunk, A_2 and A_3 are in between outer and inner layers, and A_4 is near the core of the trunk.

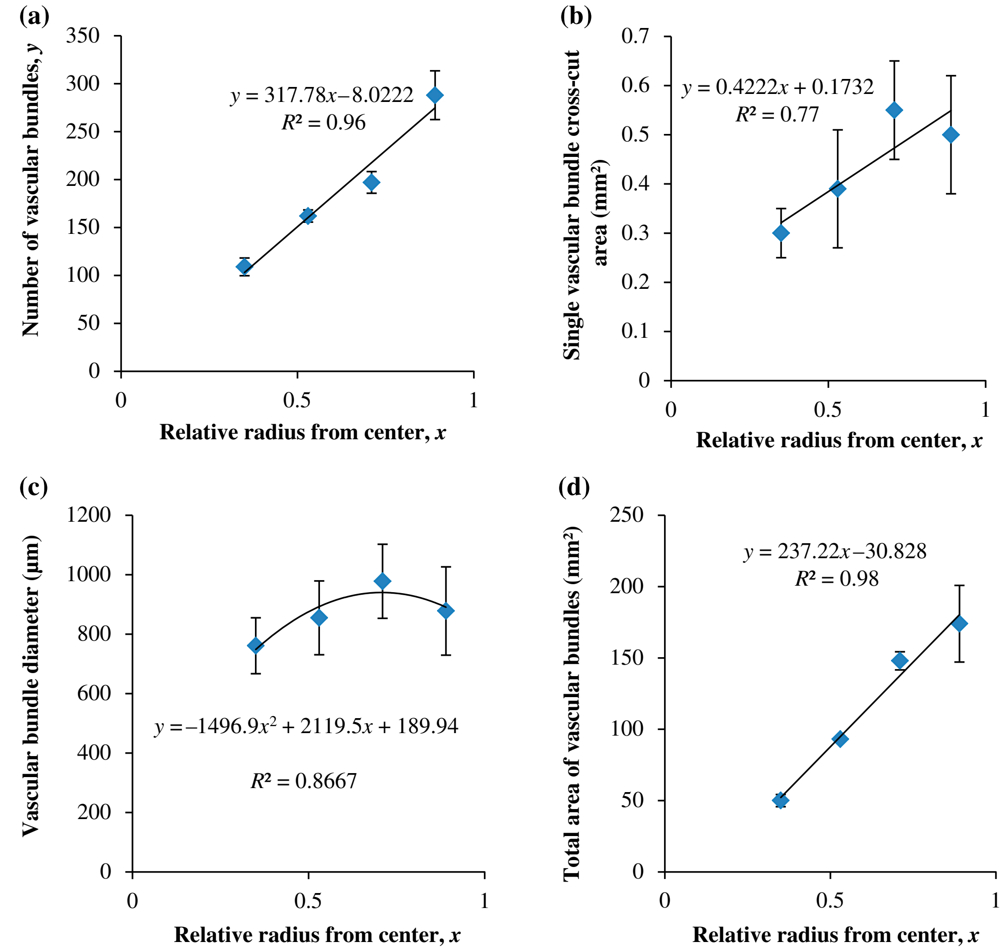

Figure 8. Anatomical properties against the relative radius from the center: (a) number of VBs, (b) single VB cross-cut area, (c) VB diameter, (d) total area of VBs.

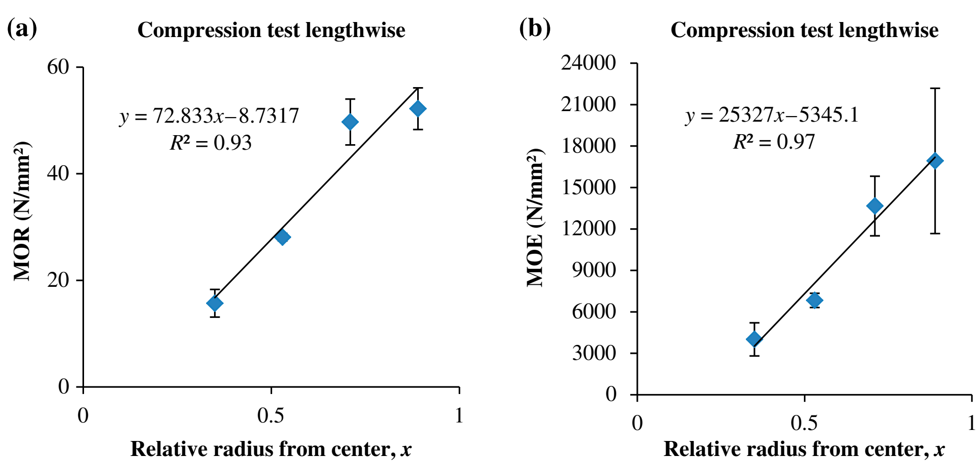

Figure 9. MOE and MOR for compression lengthwise.

The frequency of VBs varies significantly along the diameter of the trunk. The highest and lowest mean area of VBs was observed in the outer part (174.54 mm^2) and the inner part (49.59 mm^2) (based on 400 mm^2 specimen area). The graphs in Figure 8 show the anatomical properties against the relative radius from the center of the trunk. It is obvious that the relationships are well described by simple linear models. The anatomical properties near “the bark” of the trunk show higher properties than those near the

Table IV. Average mechanical properties of coconut samples (compression test lengthwise).

Samples in subsections[a]	Density (g/cm^3)	Standard deviation (g/cm^3)	MOR (MPa)	Standard deviation (MPa)	MOE (MPa)	Standard deviation (MPa)
A_1	0.80	0.02	52.2	3.9	16927	5261
A_2	0.74	0.04	49.7	4.3	13663	2154
A_3	0.49	0.02	28.1	0.7	6834	515
A_4	0.34	0.03	15.7	2.6	4007	1198

[a]Values shown are averages of four samples from each subsection; A_1 is near "the bark" of the trunk, A_2 and A_3 are in between outer and inner layers, and A_4 is near the core of the trunk.

trunk core. The VB diameter (measured in tangential direction) does not vary significantly along the trunk diameter.

Compression properties of coconut wood

In this study, only the compression properties of coconut wood are considered. Available material did not suffice tension testing. It is intended to develop a mechanical model showing the interrelation between structural features and other mechanical properties at a later stage. Test pieces were cut from the outer to inner layer (50 mm × 20 mm) as shown in Figure 1(c). A total of 16 samples were used for the test. Figure 9 shows the experimental results for compression test of coconut wood. It can be seen that the MOR and MOE are gradually increasing from the inner side to the outer side in a transverse direction.

Effects of anatomical structure and density on strength properties of wood and of single VB

The mechanical properties are presented in Figure 7 (tension strength of single VB) and Figure 9 (coconut wood). Table V gives the summary of correlation coefficients of mechanical properties over anatomical structure and physical properties of wood.

Figures 7 and 9 reveal that compression parallel to grain, the MOE and tension parallel to grain of single VB increase gradually with distance from the inner part of the trunk. The correlation presented in Table V can be rated as medium to strong.

The density of coconut wood, which is closely related to the properties of VBs and ground tissue, plays an important role in the development of mechanical properties. In Figure 10, it can be seen that first, the density of coconut wood depends strongly on total area of VBs and second, the MOR of wood depends strongly on the density and the total area of VBs. Knowing the distribution of the total area (percentage of VB from total cross-cut area) of VBs, it is possible to model density and mechanical properties of coconut wood. These relationships can easily be used for grading lumber and for the developing sawing patterns in lumber processing.

Table V. Correlation coefficients of characteristics, anatomical structures, and physical properties on mechanical properties of single VB and wood samples.

Properties	Tensile strength of VB	Compression parallel to grain
Area of VB	0.87	0.99
Number of VBs	0.78	0.90
Cross-cut area of VB	0.87	0.97
Diameter of VB	0.81	0.84
Density of coconut samples	0.83	0.99
Compression parallel to grain (CPL)	0.86	

The correlation coefficients presented in Table IV are not based on the fit using linear equation.

Further statistical analysis was conducted to study the effects of physical and anatomical characteristics on the mechanical properties, and the results are shown in Figure 11.

The analysis indicates that all properties, namely, compression parallel to grain, MOE and MOR in tension parallel to grain of single VB, highly depend on density and location in the trunk. This implies that 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). The analysis further indicates that the area of VBs is positively correlated with all strength properties. Figure 12 shows the relationship between volume fraction (vf) of VBs and MOR of wood in compression lengthwise. According to the

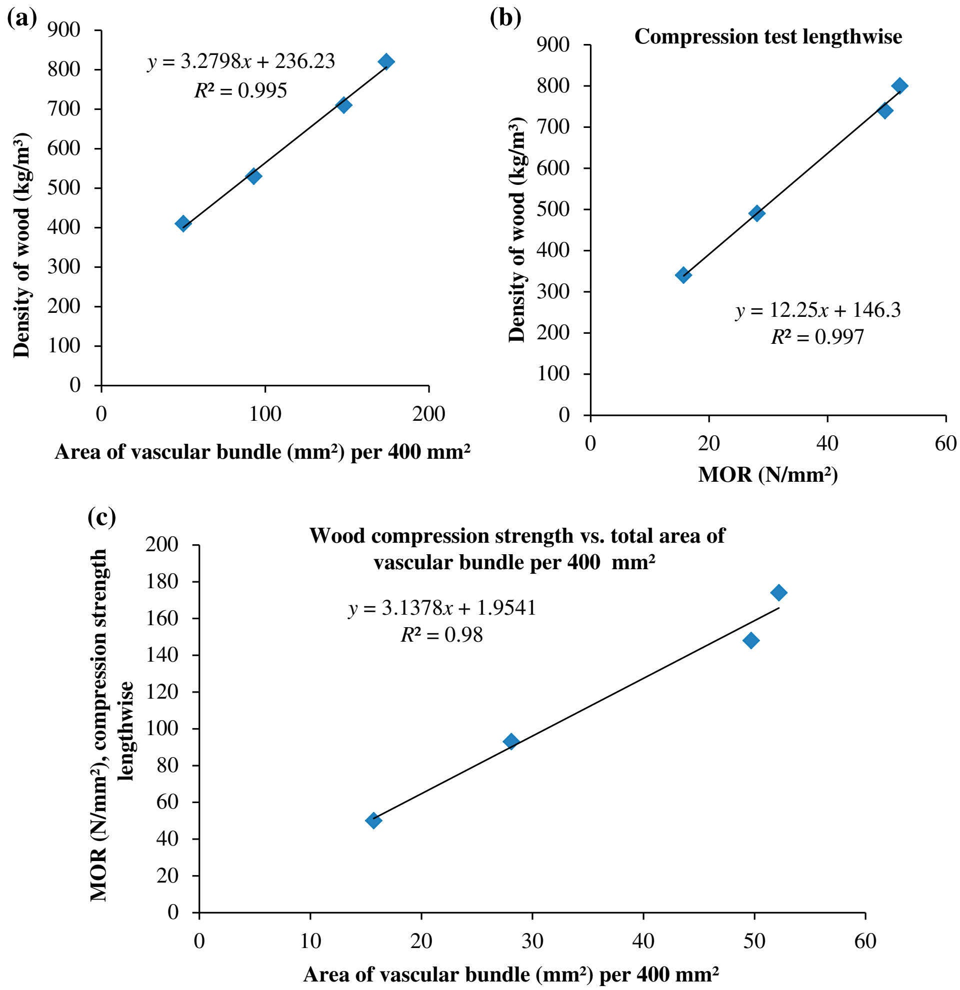

Figure 10. (a) Relationship between density of coconut wood and total area of VB (b) relationship between wood density and compressive strength parallel to grain, (c) relationship between compressive strength parallel to grain and total area of VB.

regression, the MOR of VBs (calculated with 100% vf) is 125 MPa. This value is about 40–50% of the results for MOR of VB in tension. This implies that the increase in the amount of the VBs is accompanied by increment in the greater number of sclerenchyma and conducting cells, and density and thus increases the strength properties (Sulthoni 1989). VB diameter (tangential) is positively correlated with compression strength, MOE and tension strength of single VB. This indicates that an increase in tangential diameter of VBs is accompanied by an increment of strength properties. The results also show that with increasing mechanical properties of single VB, strength properties of coconut wood increase.

Conclusions

The wood samples for anatomical, physical, mechanical (compression test lengthwise) properties and the VBs from four subsections in radial distance of the palm trunk were tested. From this study, the following conclusions can be made:

Along the cross-section, all anatomical structures near the outer side ("bark") are significantly different from those near the inner part of the trunk. All anatomical properties (quantity of VBs, VB cross-cut area, VB diameter and area of VB) increase linearly in transverse direction, from the inner part to the outer part (Figure 8).

Consequently, the density shows a significant increase from the inner to the outer part.

Compression properties parallel to grain are closely related to VB distribution and diameter which influences the density as well. The compression strength of wood samples parallel to grain, MOE and tensile strength of single VB increase linearly from the inner part of the trunk. In conclusion, the VBs vary in strength and stiffness.

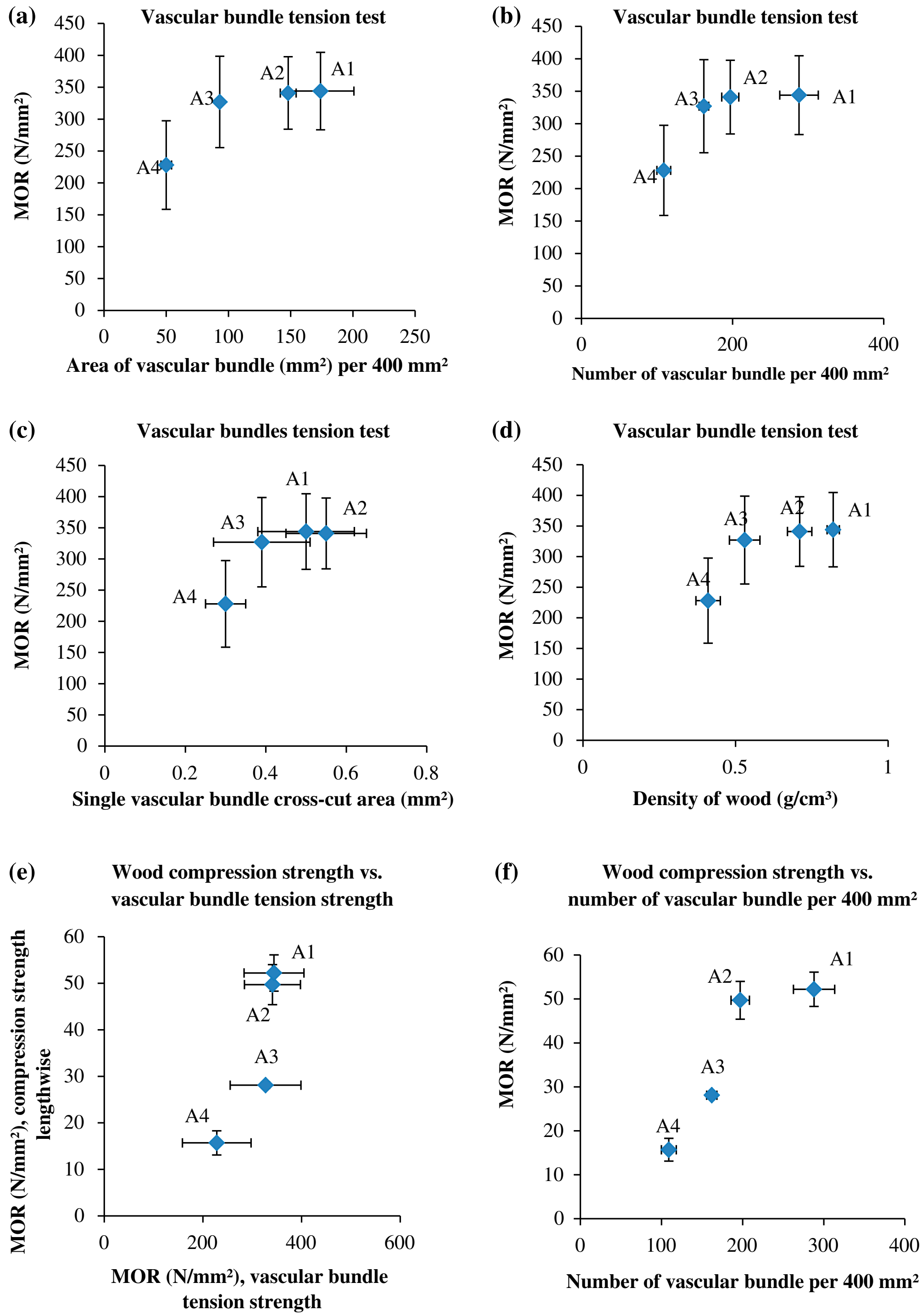

Figure 11. Effects of physical and anatomical characteristics on the mechanical properties of single VB. (a) Relationship between tensile strength of VB and total area of VBs, (b) relationship between tensile strength of VBs and number (frequency) of VBs, (c) relationship between tensile strength of VBs and square of VBs, (d) relationship between tensile strength of VBs and density of wood, (e) relationship between tensile strength of VBs and wood compressive strength parallel to grain, (f) relationship between wood compressive strength parallel to grain and number (frequency) of VBs

Along the cross-section, the density and amount of VBs near the outer part are higher than those near the inner part. Therefore, the strength also increases near the outer part with an increase of density and amount of VBs. These results are in line with findings of previous research on other preparations and additional samples that have been tested (Frühwald et al. 1992).

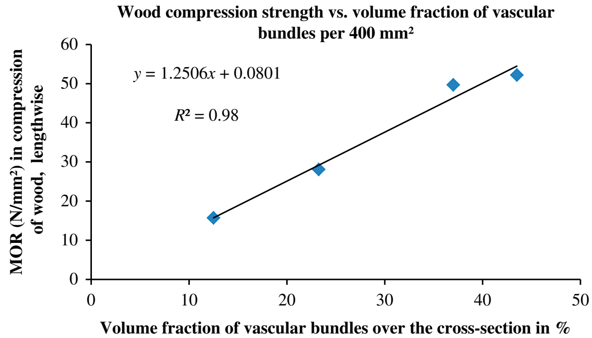

Figure 12. Relationship between compression strength parallel to grain and volume fraction of VBs over the cross-section.

Acknowledgements

The authors would like to thank Prof. Dr. Antonio Silva Guzman, *Universidad de Guadalajara*, Mexico for providing the test material and Dr. Gerald Koch (TI Hamburg) for helpful discussions and Mr. Sergej Kaschuro for his help in the preparation of fibers.

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Leila Fathi*, Arno Frühwald and Gerald Koch

Distribution of lignin in vascular bundles of coconut wood (*Cocos nucifera*) by cellular UV-spectroscopy and relationship between lignification and tensile strength in single vascular bundles

Abstract: The topochemical distribution of lignin in vascular bundles separated from different radial positions of Mexican coconut wood stems (*Cocos nucifera*) has been studied with focus on the relationship between the degree of lignification and tensile strength properties. The cellular lignin distribution was analyzed by UV-microspectrophotometry (UMSP) scanning at 280 nm of sections of vascular bundles (VBs) of 1 μm thickness. The fibers of the VBs with high tensile strength reveal a relatively low UV-absorbance at 280 nm ($A_{280\ nm}$ 0.39), whereas the VBs with low tensile strength display the highest $A_{280\ nm}$ (0.59). The S_2 of fiber walls are characterized by the typical lamellar structure with increasing lignin contents from the cell lumen towards the compound middle lamellae (CML). The $A_{280\ nm}$ data of CMLs are higher (0.67 to 0.87) than those of the S_2 wall layers. Overall, the $A_{280\ nm}$ values of S_2 of fibers walls within single VBs of coconut are in the range of 0.36 to 0.59.

Keywords: *Cocos nucifera*, dissection of vascular bundles, lignin distribution, tensile strength, UV-microspectrophotometry (UMSP), vascular bundles

***Corresponding author: Leila Fathi,** Department of Wood Science, University of Hamburg, Germany, e-mail: leilafth@yahoo.com
Arno Frühwald: Department of Wood Science, University of Hamburg, Germany
Gerald Koch: Thünen Institute of Wood Research, Federal Research Institute for Rural Areas, Forestry and Fisheries, Hamburg, Germany

Introduction

There is an increasing interest in the utilization of coconut stems (*Cocos nucifera* L.) in the copra producing regions of the world (Alston 1976). The physical and mechanical properties and anatomical characteristics of coconut wood are relevant if its industrial utilization, construction, and housing are envisaged. The density and mechanical properties of the stems are influenced by the distribution of the vascular bundles (VBs), the proportion of fibers to other cell types within the VBs, and the thickness of the cell wall of fibers and ground parenchyma cells (Butterfield and Meylan 1979). Coconut is a monocotyledon with a complex cellular anatomy of the stems, mainly composed of VBs and parenchyma cells with variable distribution. In general, the outer, middle and inner parts of the stem are distinctive. The outer part contains minor amounts of parenchyma cells and a higher share of the VBs, which are formed by vessels surrounded by a large number of fibers. The inner part contains small numbers of VBs and a higher share of the parenchyma cells. Vessel and parenchyma cells have wide lumens and relatively thin cell walls, whereas fibers are thick-walled and highly lignified. The lignin content and its topochemical distribution are of great importance for physical and mechanical properties, natural durability, and also for the utilization of wood. Wood and agricultural plants, such as wheat straw, sugarcane, bamboo, rice and linseed flax, are well investigated in this regard (e.g., Zhai and Lee 1989; He and Terashima 1991; Donaldson 1996; Koch and Grünwald 2004; Lybeer and Koch 2005; Siqueira et al. 2011; Koch and Schmitt 2013). However, little is known about the lignification and topochemical lignin distribution in coconut palm woods, which are composed of guaiacyl (G), syringyl (S), and *p*-hydroxyphenylpropan (H) units. One peculiarity of the lignin of Palmae is that they also contain large amounts of esterified *p*-hydroxy-benzoic acid (Pearl et al. 1959a,b; Suzuki et al. 1998; Gonçalves et al. 2000).

Lignin within the cell wall can be visualized by staining chemicals, UV and IR light microscopy or by electron microscopy (EM) after staining, for example by bromine. Cellular UV-microspectrophotometry (UMSP) is a very useful tool to provide general information on the topochemical distribution of lignin and phenolic extractives in the various regions of the cell wall (Fergus et al. 1969; Scott et al. 1969; Koch and Kleist 2001; Koch et al. 2003b; Mendonça et al. 2004; Singh et al. 2006; Kim et al. 2008). The technique is based on the UV irradiation of semi-thin sections (below 2 µm) of a lignified tissue, whereas lignin has absorption maxima (λ_{max}) of around 212 and 280 nm (Sarkanen and Hergert 1971). Based on the different UV-spectra of the basic lignin units, lignins from hardwoods (HW), softwoods (SW) and monocotylodones can be differentiated. SW lignins are mainly composed of G units with a λ_{max} at 280 nm, HW lignins consist of G and S units in varying ratios leading to a λ_{max} shift from 280 nm down to 270 nm depending on the amount of S units (Fergus and Goring 1970a; Takabe et al. 1992). The UV-spectra of the lignified cell walls of monocotyledons show an additional shoulder between 310 and 320 nm, which is due to the presence of 4-hydroxy-phenylpropane (H) units, which are mainly esterified with other lignin units (*p*-coumaroylation) (Higuchi 1987). As mentioned above, palm lignins also contain esterified *p*-hydroxy-benzoic acid. Most monocotyledon lignin have a λ_{max} around 280–282 nm, which is indicative for larger amounts of G units (Fergus and Goring 1970b; Musha and Goring 1975). Besides the λ_{max}, the extinction coefficient ε at λ_{max} has also a diagnostic value for identification of the lignin type based on the finding that $G\varepsilon_{280\,nm} >> S\varepsilon_{270-275\,nm}$.

To gain more insight into the topochemical lignin distribution in vascular bundles (VBs) of coconut wood, UV-microspectrophotometry (UMSP) was applied. UMSP permits the direct imaging of the lignin distribution within individual cell wall layers and also offers a variety of graphical and statistical data with a topographic resolution of 0.25×0.25 µm² (Koch and Kleist 2001; Koch and Schmitt 2013). The second aim of the present work was to relate the lignin distribution to the tensile strength of single VBs from the inner and outer trunk part. The expectation is that the considerable variation of the mechanical properties of coconut wood tissue can be better estimated in the future based on the new results.

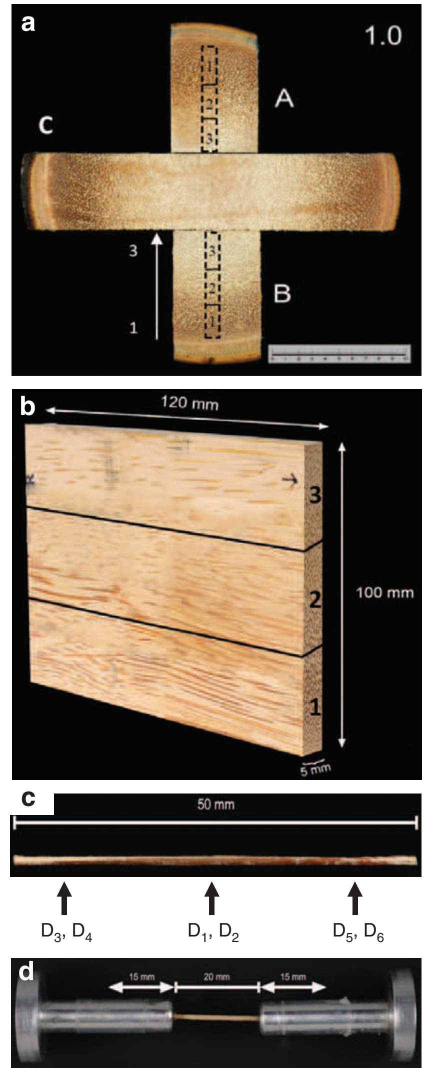

Figure 1 (a) Coconut trunk disk cut into three sections (A, B, C), (b) cutting pattern of the prepared sub-sections, (c) individualized vascular bundle (VB) for mechanical testing, $D_1 \ldots D_6$=diameter measurement points, (d) metal sample holders set up for tensile testing of a single VB.

Materials and methods

Sampling and tensile strength measurements: The coconut tree (*Cocos nucifera* L.), ca. 40 years old, was obtained from a plantation located in the western coastal region of the state of Jalisco, Mexico. A disk (30 cm in diameter) was taken at a distance of 2 m from the bottom with a 14 cm thickness. The cutting scheme of the disk is presented in Figure 1a. The sections A and B were pre-cut into three sub-sections 1, 2, and 3 each of 5 mm (t)×100 mm (r)×125 mm (l) for preparing individual vascular bundles (VBs) from the different morphological regions (Figure 1a,b).

To test tensile strength, single VBs were carefully dissected from consecutive radial positions of the indicated sections under a stereo microscope. Once the surrounding parenchyma tissue was totally eliminated, the VBs were kept straight throughout the drying process (Figure 1c). In total, 48 VBs were prepared from the three defined areas outer, intermediate and inner part of the disk (24 from section A and 24 from section B).

The cross-sectional area of the isolated VBs were measured with a caliper (accuracy 0.01 mm) at three points along the entire specimen; each measurement consisted of two perpendicular diameters, which were averaged for the calculation of the respective area. After calculation of the cross-sectional area, each of the VBs was cut to a length of 50 mm. For the tensile strength test, two pieces of aluminum sample holders were glued to the ends of the specimen and the holders were fixed in the testing device (Figure 1d).

The Zwick/Roell universal testing machine (Zwick/Roell, Ulm, Germany) equipped with a high resolution 50 kN load cell was applied. Elongation of the specimens was measured along a distance of 10 mm in the center. After the tensile test, three representative VBs with different tensile strength, two from the outer and one from the inner part, were selected for the topochemical analyses.

Cellular UMSP and anatomical parameters: A UV-microspectrophotometer (ZEISS UMSP 80, Carl Zeiss, Oberkochen, Germany), described by Koch and Kleist (2001) and Koch and Grünwald (2004), was available. The selected and mechanically tested VBs were embedded in Spurr's epoxy resin (Spurr 1969) under mild vacuum with several cycles of evacuation and ventilation (Kleist and Schmitt 1999). Sections of a nominal thickness of 1 μm were prepared with an ultra microtome equipped with a diamond knife, transferred to quartz microscope slides and embedded in glycerine.

The ZEISS UMSP 80 instrument was equipped with a scanning stage, enabling the determination of image profiles at constant wavelengths with the scan program APAMOS® (Zeiss, Jena, Germany). The observations were done at $\lambda_{280\ nm}$. The scan program digitises rectangular fields with a local geometrical resolution of 0.25×0.25 μm^2 and yields a photometrical resolution of 4096 gray scale levels which are converted into 14 basic colors to visualize the absorbance intensities. In detail, each scanning profile contains more than 25 000 individual measuring points for the detection of absorbance intensities. The recorded scans can be depicted as 2D or 3D image profiles including a statistical evaluation (as a histogram) of the absorbances. The lignification of the epidermal and hypodermal cell walls, S_2 wall layers of fibers, parenchyma cells and compound middle lamellae (CML) were measured for each of the selected VBs from the inner and outer parts, respectively.

The anatomical-structural characteristics of the coconut tissues were also studied by light microscopy (LM) (Olympus, Tokyo, Japan). The dimension of the cross sections prepared for this purpose were 20×20×20 mm^3 (Figure 2a,b). The LM was equipped with a digital camera (Olympus, SZ H10). The anatomical parameters (number of VBs, and cross-cut areas of single VBs) were determined by means of the Cell-F image-software (Olympus, Tokyo, Japan).

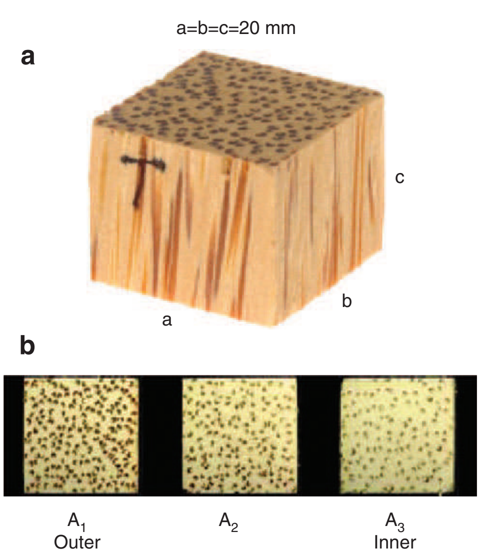

Figure 2 (a) Sample for density and anatomical tests, (b) cross-section of a coconut palm stem.

Results and discussion

General anatomy of vascular bundles (VBs)

The density of the palm wood is heavily influenced by its anatomical structure. The radial density profile of the disc investigated (Figure 3) shows remarkable decline from the outer to the inner part of the stem. A typical VB consists of vascular tissue and a fibrous sheath (Figure 4). The vascular tissue is divided into (i) xylem, composed of solitary metaxylem and protoxylem elements with xylem parenchyma, and (ii) phloem, found in two strands located on the lateral sides of the metaxylem associated with the fibrous sheath. The mean cross-cut area of the single VBs varies from 0.30 mm^2 in the inner part to 0.53 mm^2 in the outer part. As shown in Figures 5 and 6a, the VBs are bigger at the outer part than at the inner part. The differences between

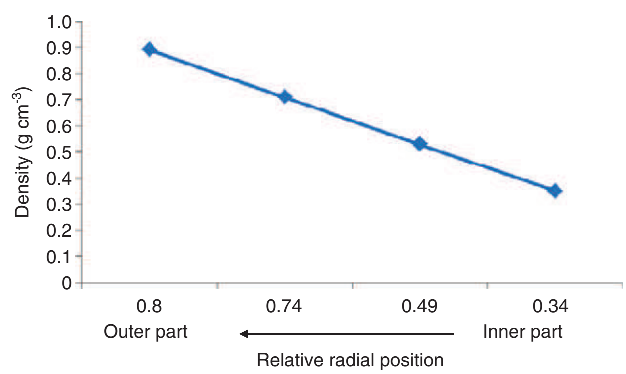

Figure 3 Density plotted against relative radial position at 2 m trunk height above the base.

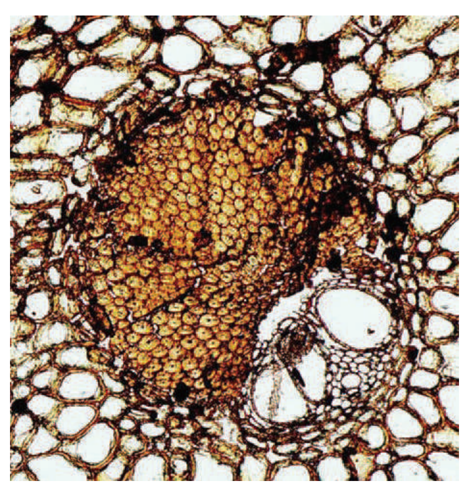

Figure 4 Representative microscopic image (transverse) of a vascular bundle of coconut palm wood with thicker walled fibers in the outer part of the trunk.

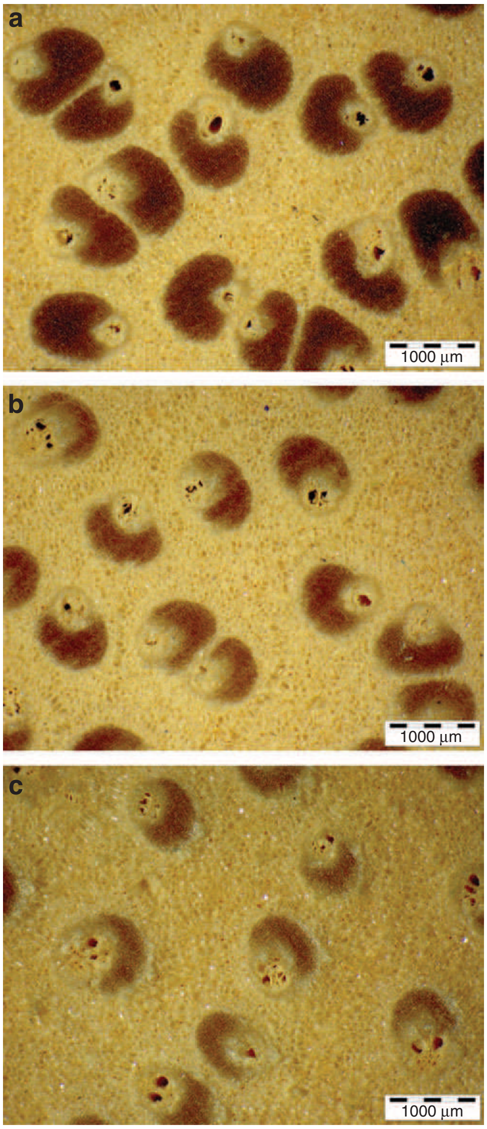

Figure 5 Macroscopic cross-sections of a coconut palm stem (a) outer part, (b) intermediate part, (c) inner part.

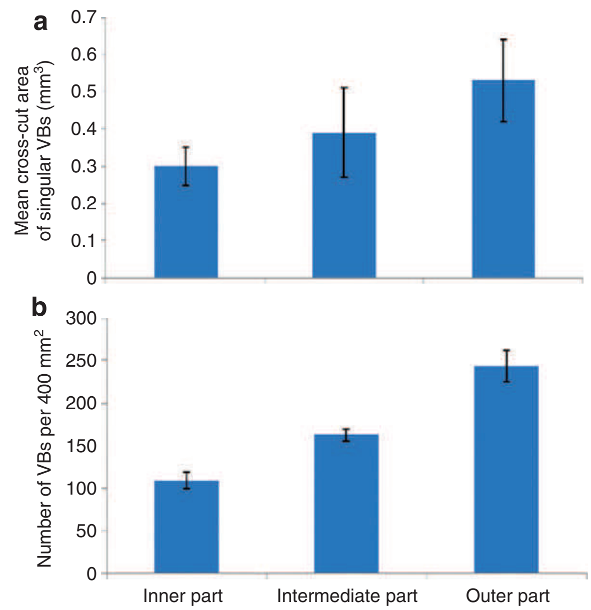

Figure 6 Data of vascular bundles (VBs) in relation to the location within the cross cut of coconut palm wood. (a) Variation in mean VBs cross-cut area. (b) Variation in mean VBs number per 400 mm².

single VBs cross-cut areas of inner and intermediate positions are not often significant. The frequency of VBs varies significantly along the diameter of the trunk (Figure 6b). The correlation coefficient (R^2) for the relationship between single VB cross-cut area and number of VBs is 0.77. There is a consistent reduction in cross-cut area of VBs with decreasing VB numbers; the samples from the outer part with high VB numbers per 400 mm² reveal the largest VBs (Figure 6a). The VB numbers differ significantly in the three different zones (Figure 5). As the single VBs cross-cut area decreases from outer to the inner part, the proportion of fibers in a bundle also decreases in the same direction. This finding is in agreement with that of Bhat et al. (1990) who demonstrated for rattan species that the fiber percentage decreases not only from the periphery to the center, but also longitudinally from the base to the top.

Proportion of fibers in a VB and fiber wall thicknesses

The density depends on the amount and cell wall thicknesses of fibers (Meylan 1978; Sudo 1980). There are more thicker-walled fibers in individual VBs of the outer part and this is the reason why the outer part of coconut wood is stiffer and more rigid than its intermediate and inner parts (Kloot 1952; Rich 1986). The inner parts with less abundance of thin-walled fibers show a tendency to break. Clearly, the size, number and composition of VBs are significant indicators for estimation of the mechanical properties of palm wood.

Tensile strength of VBs

Overall, 48 individual VBs were tested for tensile modulus of elasticity (MOE-t) and tensile strength of rupture (MOR-t) (Table 1). The representative specimens 1 and 4 (outer part) have higher tensile strength values than the specimen no. 24 from the inner part.

The MOR-t data ranged distinctly from 103 MPa to 446 MPa. The VB with the highest MOR-t value (446 MPa)

Table 1 Physical and mechanical properties of vascular bundles.

Location in stem	No. vascular bundles		Density of ascular bundles (g cm⁻³)		Tensile MOR-t (MPa)		SD (MPa)		Mean of MOR-t (MPa)		Tensile MOE-t (MPa)		SD (MPa)		Mean of MOE-t (MPa)	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Outer part	**1**	25	**0.95**	0.81	**446**	343	39	51	386	393	**33 430**	20 117	3827	4914	26 465	27 045
	3	27	0.81	0.84	382	329					28 848	27 206				
	4	28	**0.84**	0.97	**329**	441					**20 341**	32 504				
	5	29	0.82	0.95	387	445					25 781	31 900				
	6	30	0.82	0.93	384	434					24 040	25 317				
	7	31	0.87	0.81	364	381					24 924	20 079				
	8	32	0.84	0.93	357	434					27 913	30 823				
Intermediate part	9	33	0.78	0.84	309	376	41	30	365	382	24 360	21 278	2967	2784	22 962	22 834
	10	34	0.87	0.83	364	345					25 042	22 429				
	11	35	0.86	0.89	394	370					26 175	19 397				
	12	36	0.81	0.89	334	417					20 194	28 879				
	13	37	0.84	0.86	351	393					20 214	24 046				
	14	38	0.83	0.84	345	350					19 600	21 690				
	15	39	0.97	0.9	444	376					21 221	22 845				
	16	40	0.86	0.91	381	432					26 893	22 105				
Inner part	17	41	0.77	0.83	308	319	68	57	260	266	20 823	23 376	5152	3070	19 201	19 868
	18	42	0.84	0.83	282	319					17 328	22 440				
	19	43	0.73	0.84	266	315					26 501	21 937				
	20	44	0.8	0.84	257	283					19 888	20 399				
	21	45	0.78	0.84	294	244					18 577	21 716				
	22	46	0.84	0.73	249	271					13 808	16 723				
	23	47	0.75	0.78	103	217					11 451	15 204				
	24	48	**0.83**	0.74	**319**	159					**25 232**	17 145				

Samples with bold letter data were investigated by UMSP.

occurred in the outer part and, conversely, the VB with the lowest value (103 MPa) was measured in the inner part. Although, individual values varied considerably, the average values of both MOE-t and MOR-t decreased gradually from the outer to the inner radial position of the stem.

The relationship between MOE-t and MOR-t of the tested VBs is illustrated in Figure 7. Obviously, this relationship can be described well by a simple linear model showing a positive trend (R^2=0.55 section A and R^2=0.50 section B). The same relationship is presented in Figure 8 as a function of the radial distance of the VBs from the center in section A. The VBs near the bark have higher tensile strength and Youngs modulus than those near the core (Figure 8). The variation of the strength can be expressed by the linear equations presented in Figure 8a,b, respectively.

As seen in Table 1, there is no distinct difference in the mechanical properties between the selected sections A and B. The congruent results of the physical and mechanical properties indicate no significant differences in chemical composition or structure of the VBs on the opposite sides. Therefore, the topochemical lignin distribution was only investigated from the inner and outer parts with one representative radius of the sample series A. Therefore, the specimens with the highest MOR-t value (no. 1, 446 MPa) and the lowest MOR-t value (no. 4, 329 MPa) from the outer part and the specimen with the highest MOR-t value (no. 24, 319 MPa) from the inner part of section A were selected for the topochemical analyses.

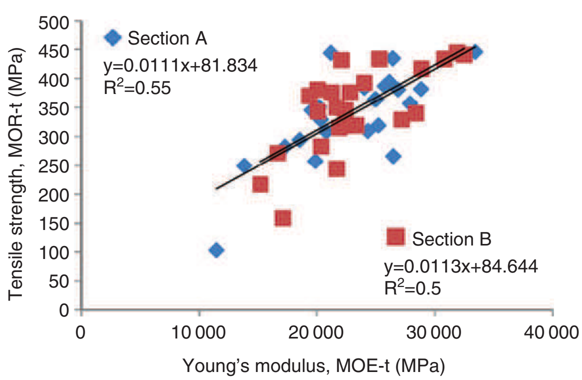

Figure 7 Relationship between MOE-t and MOR-t in the tested vascular bundles.

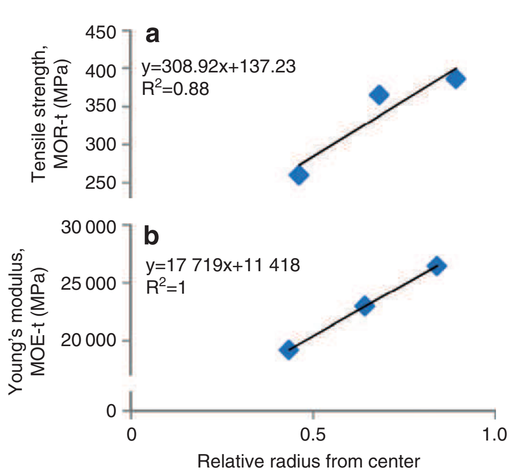

Figure 8 Variation of (a) tensile strength (MOR-t) and (b) Young's modulus (MOE-t) of vascular bundles along the radius.

Topochemical distribution of lignin in individual VBs

In Figure 9, the UMSP data measured at $\lambda_{280\ max}$ of the S_2 of polylamellated fiber walls in VBs are displayed. The typical lamellation is generally described as alternating broad and narrow layers with different fibrillar orientation (Koch and Schmitt 2013). The evaluation of the UV-image profiles shows distinctly high UV-absorbances ($A_{280\ nm}$) of the CML and cell corners (CC) ($A_{280\ nm}$ 0.65 to 1.00) for all fibers of the individual specimens (no. 1 and no. 4 from the outer part, no. 24 from the inner part). The CML and CC are clearly visualised by green and yellow, which represent high UV-absorbance. In contrast, the $A_{280\ nm}$ values of the S_2 layers differ significantly between the outer stem (0.39 to 0.43, red color of the S_2 cell walls) and the inner stem (0.59, turquoise color of the S_2 cell walls). The presented data for both morphological regions are based on the statistical evaluation of more than 32 000 measuring points (Table 2), and indicate a significantly higher lignification of the S_2 in the VBs from the inner part of the coconut stem. The averaged UV-absorbances are summarized in Table 2.

The distinct topological differences in the lignification of the VBs were further documented by the evaluation of individual UV-line scans from different locations (Figure 10). The numerical data collected from the outer regions (Figure 10a) are much lower than those from the inner regions (Figure 10b). Furthermore, the statistical evaluation (see histograms) of the scanned fiber cell walls shows a distinct shift to higher UV intensities toward the VBs from the inner part.

Vessel elements were also observed by UMSP. Figure 11a shows a representative UV-image profile of a part of a vessel wall adjacent to a fiber and parenchyma cell selected from the inner region. Especially, very high $A_{280\ nm}$ values are typical for the CC and CML regions. The black in the images indicates an overflow with extinctions

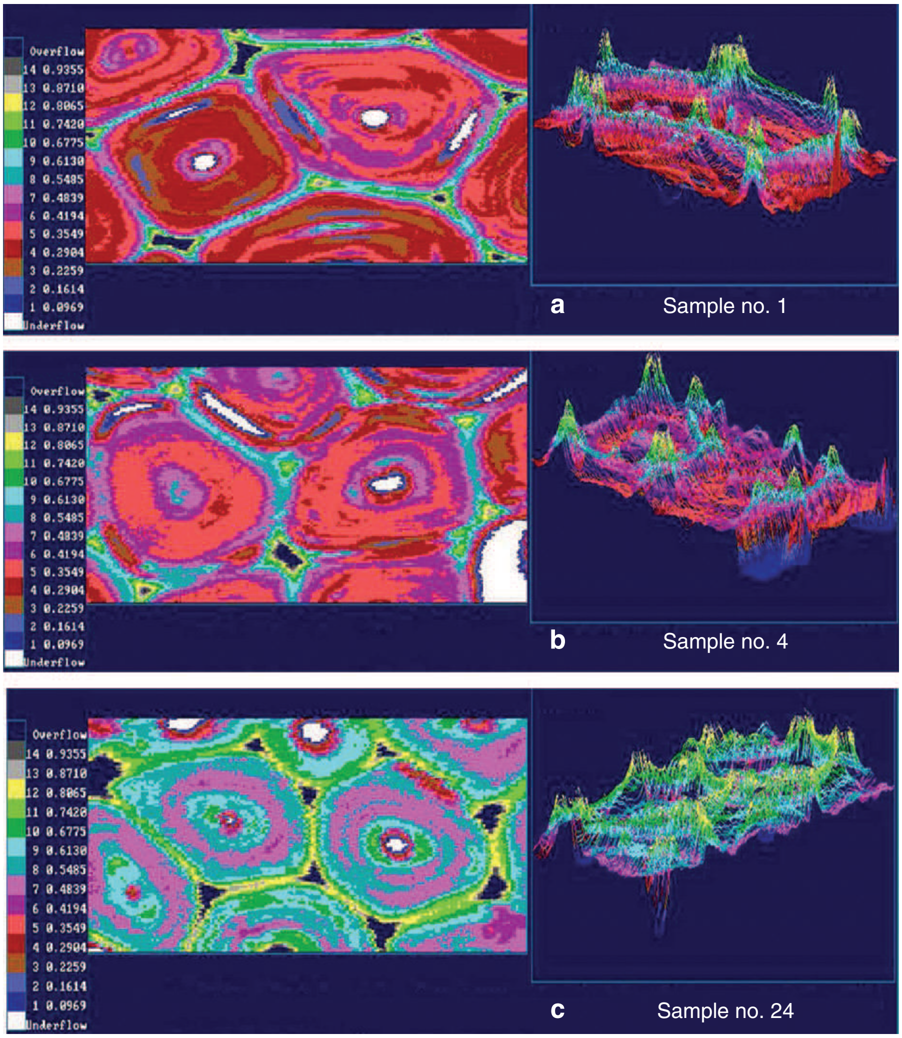

Figure 9 UV-scanning profiles of cross sections of three vascular bundles. They show a progressive stage of lignification from specimen 1 (a) to 4 (b) to 24 (c). The individual color pixels represent $A_{280\ nm}$ data.

Table 2 Average UV absorbance ($A_{280\ nm}$) at the cross section of the selected vascular bundles.

Specimen no.	Number of pixels per (0.25×0.25 µm²)	Area 10^3 µm²	Mean $A_{280\ nm}$[a]
1	12 027	0.75169	0.41
	11 132	0.69575	0.47
	49 350	3.08437	0.36
	54 756	3.42225	0.39
4	20 474	1.27963	0.44
	24 332	1.52075	0.40
	46 097	2.88106	0.45
	36 608	2.28800	0.43
24	11 180	0.69875	0.49
	15 300	0.95625	0.52
	36 696	2.29350	0.51
	32 073	2.00456	0.59

[a]Collected from several areas in vascular bundles.

above 1.0. In contrast, a comparable image profile of a vessel wall adjacent to parenchyma cells (Figure 11b) from the outer region display less UV intensities. Accordingly, these results confirm the observations concerning the higher degree of lignification of cells situated in the inner regions (Figures 9 and 10).

In general, the UV intensities for CC and CML ($A_{280\ nm}$ 0.68 to 0.92) are higher than those from adjacent S_2-layers ($A_{280\ nm}$ 0.35 to 0.62) and confirm again the well-known high lignin concentration in CC and CML. The $A_{280\ nm}$ data of the CCs are about twice of that in the S_2 of the fibers. These observations are in agreement with literature data collected from other woody tissues (Fergus et al. 1969; Scott et al. 1969; Koch and Grünwald 2004; Singh et al. 2006). The cell walls of parenchyma cells are apparently less lignified.

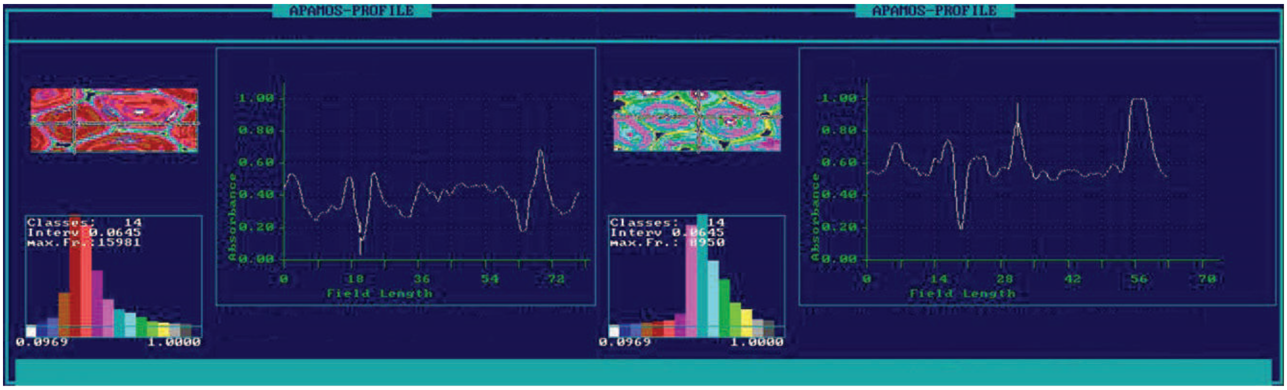

Figure 10 UV microscopic scanning profiles of vascular bundles from outer and inner radial position scanned with a geometrical resolution of 0.25×0.25 μm². The color scales indicate the $A_{280\ nm}$ data.

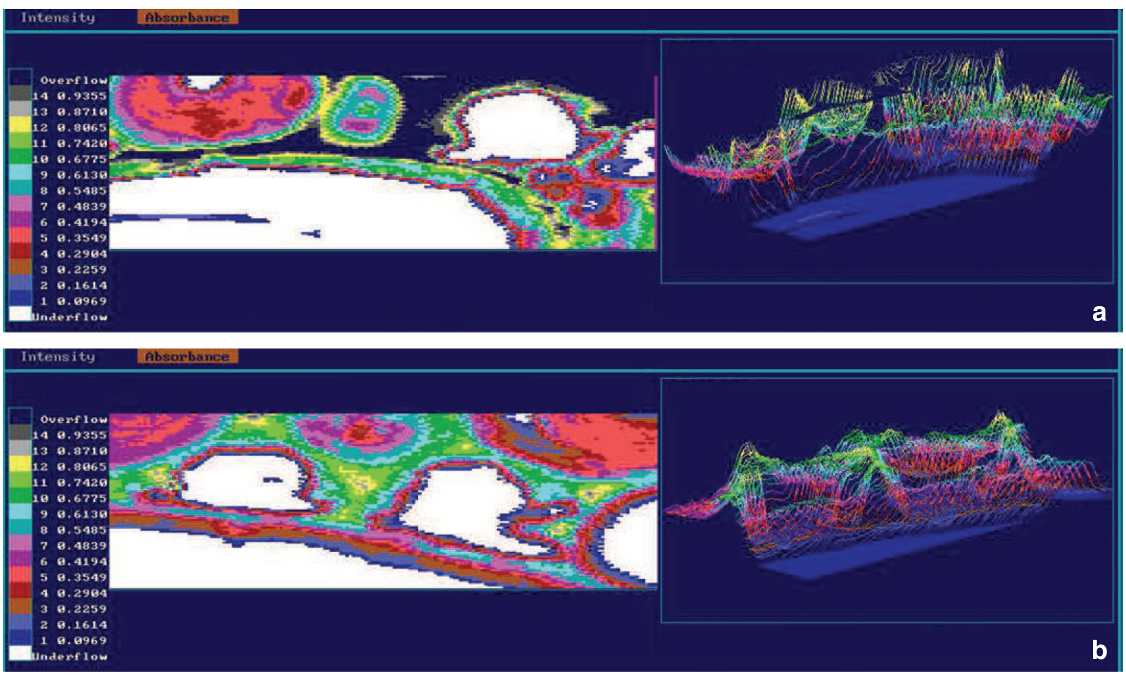

Figure 11 (a) UV-scanning profile of a part of vessel wall adjacent to fiber and parenchyma cells from the inner part of the coconut stem. The color-pixels display the $A_{280\ nm}$ data with high intensities in the region of the cell corners and compound middle lamellae, (b) UV-scanning profile of a part of vessel wall adjacent to fiber and parenchyma cells from the outer part of the coconut stem. The color-pixels indicate lower $A_{280\ nm}$ values compared to those from the inner regions.

Effects of lignin and cell wall thickness on tensile strength of VBs

It is known that higher lignin content results in lower tensile strength but higher compression strength (Bamber 2001). Table 3 shows the relationship between tensile strength of the tested VBs and the average $A_{280\ nm}$ data of the fibers. Tensile strength is negatively correlated to the lignin content based on the $A_{280\ nm}$ data. However, the statistical evaluation revealed a weak correlation (R^2=0.48), which can be interpreted that other parameters are also effective, mainly the anatomical parameters, i.e., proportion of fibers in a vascular bundle, cell wall thickness and microfibril angle in the cell wall layers.

Coconut palms can grow to stem heights of 20–40 m. Unlike SW and HW trees, palms lack cambium and strengthen their stems by adding additional layers to the cell walls in the VBs, which improve the mechanical

Table 3 Relationship between tensile strength of vascular bundles and the average UV absorbance ($A_{280\ nm}$) at the cross section of single vascular bundles.

Sample no.	Tensile MOR-t (MPa)	Mean $A_{280\ nm}$
1	446	0.39
4	329	0.43
24	319	0.59

Table 4 Approximate composition of tracheid cell wall from softwoods (by dry weight) (according to Bodig and Jayne 1982).

Cell wall layer	Cellulose (%)	Hemi-celluloses (%)	Lignin (%)
Primary	15	15	70
S_1	28	27	45
S_2	45	35	20
S_3	47	38	15

properties. According to Gibson (2012), the concentration of VBs as well as the concentration of fibers within the VBs is greater at the outer part of the trunk than in the inner part. The same is true for the cell wall thickening. SEM images of coconut palm wood indicate that the thicker cell walls have additional secondary layers (Figure 12a,b), which was also found by Kuo-Huang et al. (2004). According to Bodig and Jayne (1982), the composition of the cell wall varies through the four layers, with the highest fraction of lignin in the primary layer and the highest fraction of cellulose in the S_2 layers (Table 4). Based on these results, it can be summarised that the VBs in the outer part have additional secondary layers, a higher concentration of cellulose and therefore a higher tensile strength as compared with the VBs in the inner part of the trunk. However, the limited number of the prepared and tested VBs may affect the non-linear regression between measured tensile strength and spectroscopically detected lignification. Nevertheless, it is generally accepted that cellulose is mainly responsible for tensile strength in wood because of its special microfibrillar structure (Winandy and Rowell 1984).

Rüggeberg et al. (2008) have investigated the stiffness gradients in VBs of the palm *Washingtonia robusta* (H. Wendl.) and stated that changes in cell cross-sectional area and cell wall thickness result in a decrease in density towards the periphery of the fiber caps. Furthermore, the authors concluded that changes in the degree of orientation of the cellulose microfibrils did not reveal any visible trend, and a gradient in lignification and a change in lignin composition most probably have an effect on the shear behavior of the matrix, which in turn influences the cell wall stiffness. These findings point to an additional concept of how plants control and change the stiffness of their tissues, besides the well-known strategy of changing the orientation of cellulose microfibrils in the secondary cell wall layers.

The presented results indicate that MOE-t and MOR-t in tension parallel to the grain of single VBs depend on the degree of lignification of the fiber walls of the VBs. This implies that a decrease in lignification may shift the strength of the material under tension towards the cellulose wall component. The variation of mechanical

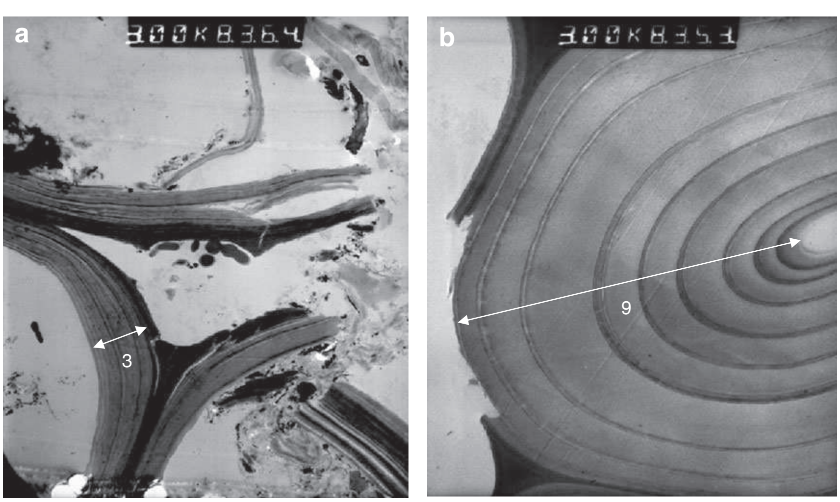

Figure 12 Scanning electron micrographs of cross sections of coconut palm wood showing cells near (a) the centre of the stem with a primary layer and one secondary layer and (b) the periphery of the stem with a primary cell wall and several secondary layers.

properties is also affected by density. However, the density data (Table 1) show that the VBs in different topological regions are not extremely different in this regard.

Conclusions

Cellular UMSP provided a detailed view of the topochemical distribution of lignin within the individual cell wall layers of VBs of coconut wood. The UMSP measurements revealed quantitative differences in the lignification of the VBs from the outer and inner stem section. Tensile strength increased with a decreasing degree of lignification. It is reasonable to conclude that in the case of a lower lignin content the cellulose moiety of the cell wall is higher.

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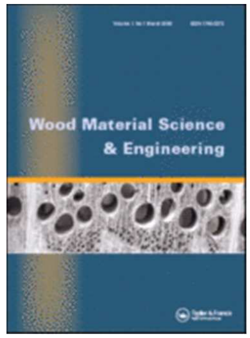

Environmental-friendly short-term protection of palm wood against mould and rot fungi

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Keywords:	Wood Protection, Biological control of wood quality < Wood quality

Environment-friendly short-term protection of palm wood against mould and rot fungi

M. BAHMANI[1], O. SCHMIDT[1], L. FATHI[2] & A. FRÜHWALD[2]

[1]*Section Wood Biology, Centre of Wood Sciences, University of Hamburg, Hamburg, Germany and* [2]*Section Mechanical Wood Technology, Centre of Wood Sciences, University of Hamburg, Hamburg, Germany*

Running title: Palm wood protection against moulds and rot

Abstract

Felled palm trunks are susceptible to fungi as long as their moisture content is above fibre saturation. During this period, palm wood has to be protected against mould and rot fungi. The study was aimed at testing environmental-friendly organic acids for their protecting efficiency. Small samples of Date palm (*Phoenix dactylifera*) and Oil palm (*Elaeis guineensis*) wood were treated with weak organic acids and subsequently infected by moulds and wood-decay fungi. Short dipping of the samples in solutions of 5% acetic acid and propionic acid, respectively, protected all samples for two months from colonization by *Aspergillus niger*, *Penicillium* sp., *Cladosporium* sp., and by a natural infection. Boric acid (4%) used in practice for protection was ineffective. Decay tests with the white-rot fungus *Pleurotus ostreatus*, the brown-rot species *Coniophora puteana* and the soft-rot fungus *Chaetomium globosum* showed that both acids prevented most samples from fungal colonization for three weeks and reduced the decay considerably during two months.

Keywords: Phoenix dactylifera, Elaeis guineensis, *mould infection*, *rot*, *protection*, *acetic acid*, *propionic acid*, *boric acid*

Introduction

Most palms (Arecaceae, Monocotyledoneae) grow in warm regions, where they supply the people with a large manifold of products, food and animal feed. The true date palm (*Phoenix dactylifera*) and the Canary Island date palm (*P. canariensis*) grow in arid and semiarid areas, particularly in Egypt, Saudi Arabia, Iran, United Arab Emirates, Pakistan, Algeria, Sudan, Oman, Libya, and Tunisia (Raj Bhansali 2010). The African oil palm (*Elaeis guineensis*) and the American oil palm (*E. oleifera*) are mainly cultivated in Indonesia, Malaysia, Thailand, Nigeria, Colombia, Ecuador and Papua New Guinea (FAO 2009). The oil extracted from fruits and seeds is used for food and chemical and pharmaceutical products as well for biodiesel.

The trunk of palms is enveloped by an outer cortex made of parenchyma cells and fibres, and the centre consists of vascular bundles (Darvis *et al.* 2013; Fathi and Frühwald 2014; Fathi *et al.* 2014) embedded in parenchymatous ground tissue (Ramle *et al.* 2012). For oil palm, the wood density varies from 100 kg/m^3 (oven dry) in the upper inner part of trunk to 900 kg/m^3 in the lower peripheral part of the trunk (Erwinsyah 2008). This high density variability is accompanied by similar variability of mechanical properties and is the reason why the wood is currently only used in very small quantities for lightweight products, insulation, sandwich boards, packaging and furniture. However, research is currently done to explore the potential uses of this lignocellulosic resource.

Further to the density variation a particular characteristic of palms is the initially high moisture content in the trunk. In oil palms, it increases with the increasing amount of parenchyma tissue from the periphery to the centre and from the stem base to the top until 400% (Lim and Khoo 1986). Additionally, the content of free sugars (from 75% methanol extract) in the wood is high, for oil palm of up to 9% based on oven dry mass (Khoo *et al.* 1991). Parenchyma cells are a suitable substrate for many microorganisms (Schmidt 2006). Therefore, as other lignocelluloses, the felled trunk with its high parenchyma and moisture and sugar content is susceptible to the colonization by mould fungi (Deuteromycetes) and decay fungi (Basidiomycetes, Ascomycetes) until the wood has dried down below fibre saturation of approx. 30% moisture content. Mould infected products are not accepted by the consumers and rot changes the colour and reduces wood strength properties.

Several successful experiments to protect lignocellulosic substrates against microorganisms by organic acids have been performed in our Institute. Sugarcane bagasse, the fibrous residue of *Saccharum officinarum* after extraction of juice, used for the production of particle board and pulp, was prevented from moulds by spraying it with organic acids (Liese and Walter 1978). Against the discolouration of oakwood by the soft-rot/mould fungus *Paecilomyces variotii*, a treatment of the fresh wood with 5-10% propionic acid was recommended (Bauch *et al.* 1991). Dipping fresh boards from the light African Ilomba (*Pycnanthus angolensis*) wood in 5% solutions of formic acid and propionic acid, respectively, prevented the brown discolouration by bacteria (Schmidt 2006). Bamboo wood samples were protected from mould growth after dipping in solutions of 10% acetic acid and propionic acid, respectively (Tang *et al.* 2009, 2012). However, Welling and Lambertz (2008) obtained mould and blue-stain protection of pine sapwood samples by dipping it in 7.5 and 10% solutions of potassium and sodium carbonate (pH 11 – 12), but only in combination with heat-treatment. In Malaysia, boric acid is used in practice to protect oil palm wood.

To develop an improved protection technique for palm wood which is environmentally friendly for the use in open areas like plantations and sawmill log yard, experiments were performed with samples of trunk wood of different densities from date and oil palm treated with acids and subsequently infected with mould and wood-decay fungi.

Materials and methods

Palm wood samples

Frozen trunk sections of date palm (*Phoenix dactylifera* L.) from Southern Iran and oil palm [*Elaeis guineensis* (Kunth) Cortés] from Southern Thailand and were sectioned to samples with a cross-section area of 20 x 20 mm and 10 mm in fibre direction for the mould test and 7 mm for the decay experiment with various rot fungi. Due to anatomical differences within the trunk, particularly the amount and distribution of vascular bundles over the stem height and cross section of the palm (Lim and Khoo 1986, Fathi 2014, Fathi and Frühwald 2014, Fathi *et al.* 2014), samples were taken from the bottom, middle and top part of the trunk as also within each trunk cross-cut area from the inner, middle and outer part so that nine variables were considered. For the mould test, one series ("dried") comprised samples which were dried at 60^{o}C for 24 hours in order to absorb more dipping solution. A second series ("fresh") simulated more practical conditions using samples of higher moisture content, which had been only shortly thawn after storage in a freezer. Wood samples of beech (*Fagus sylvatica* L.) and pine (*Pinus sylvestris* L.) served as controls. Samples for the decay test were dried at 103^{o}C to measure their initial dry mass for final mass loss determination.

Treatment with acids and sample preparation

Of the nine palm trunk variables from each date and oil palm and the beech and pine wood controls, numbered and grouped samples were dipped for 10 min in tap water (control) and in tap-water solutions of 5 and 10% acetic acid (Merck) and propionic acid (Merck), respectively. Tap water was used instead of distilled water to avoid extraction of ions from the fungal cells used for inoculation and in view of the practical application of the technique under field test conditions. For comparison, 4% (maximum solubility in water) boric acid (Roth) was used. For the decay test with more slowly growing Basidiomycetes and Ascomycetes, the untreated palm and wood controls were autoclaved at 2.1 bar and 121^{o}C for 18 min to avoid mould infections of the not-chemically preserved samples before placing them in Petri dishes on the grown mycelia. The acid-dipped samples were not sterilized due to their assumed protection against moulds to avoid heat influences on the acids by autoclaving.

Fungi used

The moulds used had been isolated from the soil of pot-plants in the Institute by streaking soil particles on malt agar dishes (2% malt extract, 1.5% agar, Oxoid). After subculturing to pure cultures, moulds were macro- and microscopically identified to the species or genus level. The rot fungi derive from the strain collection of OS (Table 1).

Sample inoculation and incubation

The mould test was performed in plastic jars each with a set of the nine palm trunk variables of both palm species, either untreated or dipped in 5 and 10 % acetic acid as well in 5 and 10% propionic acid (Figure 1, left). The moulds were pre-cultured on malt agar plates for approx. one week until the agar surfaces were covered by a dense layer of spores (conidiospores). For spore sampling, the Petri dishes were flooded with sterile tap water removing the spores from their conidiophores with the help of an inoculation loop. Each palm wood sample was inoculated on its upper surface with one drop (approx. 10 µl) spore solution. Its subsequent microscopy revealed that 50 to 100 spores had been present in 10 µl. Inoculated containers were closed and cultured at 23^{o}C up to two months. One sample series initially remained open for some hours to become infected by air-borne spores from the laboratory. To simulate the permanent infection pressure by air-borne spores under natural conditions, the artificially and naturally infected 5% acid-treated oil and data palm samples were infected a second time after four weeks.

The decay test was done in Petri dishes with malt agar (Figure 1, right) inoculated with mycelial agar plugs from approx. two weeks old pre-cultures of *Pleurotus ostreatus* (Jacq.: Fr.) Kummer and *Coniophora puteana* (Schum.: Fr.) P. Karsten (Table 1). For inoculation with *Chaetomium globosum* Kunze: Fr., a suspension of ascospores was sampled from the pre-culture by disrupting the grown fruiting bodies (perithecia) with an inoculation loop. Five samples (one control and each one dipped in the four solutions) were placed directly on the mycelia and fruiting bodies (Figure 1, right). Three parallels of each trunk variable, acid treatment and fungus were used. For one series, samples were additionally placed on sterilized metal rings as supports like in EN 113 (1996) to avoid direct contact between acid and fungus. Altogether, approx. 1.600 samples were included. Incubation was at 23°C for two months.

Sample evaluation

Mould growth was macroscopically evaluated in regular intervals using a grading from 0 (no growth) to 3 (sample totally overgrown with mycelium and/or dense spore layer). Samples of the decay test were dried at 103°C after two months of incubation, and the percentage of mass loss was calculated according to EN 113. To consider the possible influence of the uptake of chemicals (acids) on the final percentage of mass loss, additional samples were weighed for the initial and final wood dry mass with intermediate dipping in acid solutions.

Activity tests of spores

The germination ability of the conidiospores of the three mould species placed on the surface of acid-treated palm wood samples was tested after three weeks of incubation by taking spores from the treated sample surface by (1) streaking an inoculation loop first over the palm sample and then over fresh malt agar plates, (2) making a stamp made from an autoclaved cotton plug and touching first the sample and then agar plates, (3) placing treated samples upside down on agar plates. To test the surviving of spores (fungicidal effect) in the acid environment of the treated samples, freshly sampled spores were suspended in 10% acetic acid and propionic acid, respectively, for 15 min and four hours and thereafter 100 µl spore solution was plated on agar. To consider that also acid solution will be transferred by this procedure, which may inhibit growth on the plates, additionally, the solution was previously diluted 1 : 50 with tap water.

Results and discussion

Mould prevention

Unprotected palm wood is rapidly colonized and discoloured by moulds and blue-stain fungi. For the experiments to prevent moulds, the considerable variation in the anatomical structure, density and initial moisture content of the wood tissue within a palm trunk was covered by the test design (Figure 1 left). However, there were no detectable differences in mould susceptibility between samples from the trunk bottom, middle and top or from their central, medium and outer wood areas. Initially, it had been also assumed that the "dried" palm samples would be better protected against moulds than the "fresh" ones due to more liquid absorption by the dry tissue. However, the differences between dried and fresh samples were small. Probably, greater differences would occur if lower-concentrated acid solutions were applied. Obviously, all sample conditions tested were within the physiological range for moulds. Therefore, Table 2 groups the data only according to palm and fungus species.

Most control samples, either infected by mould pure cultures or by air-borne spores, were colonized within two weeks. It can be assumed that the same initial vitality occurred when the spores contacted the acid-treated samples.

All samples from date and oil palm dipped in solutions of acetic and propionic acid were still free from moulds after eight weeks of incubation, even at the low 5 % acid concentration (Table 2). The wood moisture content of the "dried" samples was below fibre saturation after four weeks of incubation, which means that the critical phase for mould infection and growth was finished. The "fresh" samples contained still enough moisture for moulds at that time. Therefore, the infection of these samples was repeated after four weeks, to simulate the permanent infection pressure in nature. Even so, there was no mould growth after altogether eight weeks of incubation. Also the samples naturally infected once again did not show mould growth after eight weeks. Obviously, the surface of the treated samples was too acid for mould colonization during the critical phase of high moisture content. The moisture content after eight weeks was below 30%.

Borax/boric acid mixtures are used in Asia for mould protection of bamboo culms for overseas transport and storage. However, mould-infected culms often arrive in Europe and laboratory tests revealed only low protective effect of boron compounds against moulds (Tang *et al.* 2009). Boric acid is also applied in Malaysia to protect oil palm wood in practice. Table 2 shows that boric acid did not protect the palm wood samples. The infected samples showed mould growth already after three days. The pH-value of 5.3 of the 4% boric acid solution is suitable for fungal growth.

It is general knowledge that spores can resist adverse conditions and subsequently germinate to mycelium in suitable environments. For some fungi, the duration of the germination ability was found to be long, for example up to 20 years for *Serpula lacrymans* (Grosser *et al.* 2003). Nevertheless, to consider natural conditions it was of interest if the spores used were still alive and could germinate after longer contact with the acids. Furthermore, the samples were infected only twice and the incubation was done in closed jars and dishes, whereas, in practice, acid-treated palm wood will be permanently opposed to air-borne spores. To consider both aspects, spores were re-sampled from some treated samples after three weeks of incubation and put on fresh malt agar. None of the three moulds (Table 1) taken from samples treated with 10% acetic and propionic acid, respectively, germinated on fresh agar, which means that the spores either had lost their germination ability or were no longer alive.

Acetic acid, either chemically pure or as vinegar is one of the oldest and most widespread preservatives of animal feed and food against bacteria, moulds and yeasts. Concentrations of 0.02 - 0.04% inhibited several bacteria and 0.02 - 0.09% were lethal; the yeast *Saccharomyces cerevisiae* was inhibited by 0.59% acetic acid and the mould *Aspergillus niger* by 0.27% (Levine and Fellers 1939). Concentrations of 2 – 9%, which are used as household vinegar, are bactericidal to sporeless bacteria (Wallhäußer and Schmidt 1967). Propionic acid has been proven to show the broadest antimicrobial activity (Woolford 1975). It is used since decades in feed preservation and is registered in the United States as a fungicide and bactericide for indoor and limited outdoor use to control fungi and bacteria in stored grains, hay, corn silage etc. (Kung *et al.* 1998, Haque *et al.* 2009). It occurs naturally in in dairy products (up to 1% in Swiss cheese) and is a normal component of metabolism in the human body (R.E.D.Facts 1991). The inhibition effect was enhanced as the pH-value declined (Woolford 1975). Therefore, the effect of both acids is complex, due in part to the hydrogen ions and in part to the undissociated molecules of the acids but the influence of the latter is much greater than that of the former (Levine and Fellers 1940). In solution, weak acid preservatives exist in a pH-dependent equilibrium between the undissociated and dissociated state. The inhibitory activity is optimal at low pH-value because this favours the uncharged, undissociated state of the molecule which can freely permeate across the plasma membrane; inside the cell the molecule dissociates resulting in the release of charged ions and protons (Brul and Coote 1999). Therefore, growth inhibition by weak acid preservatives has been proposed to be due to a number of actions including membrane disruption, inhibition of metabolic reactions, stress on intracellular pH homeostasis and the accumulation of toxic anions (Brul and Cote 1999). Correspondingly, preservation experiments on bamboo wood against moulds in the laboratory (Tang *et al.* 2009) and in the tropical climate of Vietnam (Tang *et al.* 2012) have shown the influence of the specific acid because dipping in solutions of 10% acetic acid and 10% propionic acid, respectively, prevented mould growth, while other acids, like boric, citronic, formic and sorbic acid, were ineffective. The influence of the undissociated molecule/acid pH-value became obvious because acetic acid and propionic acid solutions of approx. pH 2.9 were effective and those of Na-acetate and Na-propionate (pH 8.1 and 8.5) were not. Tekelenburg (1927) demonstrated that the alkali salts alone had no marked bactericidal effect. Therefore, growth inhibition of mould and blue-stain fungi on pine wood samples by dipping in solutions of potassium and sodium carbonate (pH 11 – 12) was only effective in combination with heat-treatment (Welling and Lambertz 2008).

Data on the fungicidal effect of both acids on spores of the three mould species used were not available. The viability test performed in view of any fungicidal effect showed that most spores of *A. niger*, *Penicillium* sp. and *Cladosporium* sp. had lost their ability to germinate after only 15 min stay in both acid solutions, even after diluting the acid concentration 1 : 50 before spore transfer on agar. Only one spore of *Aspergillus niger* and four spores of *Penicillium* sp. from the 15 min-suspensions in acetic acid germinated on fresh agar, however needing teen days, whereas the untreated control spores germinated within three days. There was no germination after suspending spores for four hours.

Although the moulds used derive from a German habitat, it can be assumed that those or similar species and genera occur also in the native environments of palm trees, particularly because *Aspergillus* and *Penicillium* species are very common with worldwide distribution (e.g., Samson *et al.* 2004, Schmidt 2006).

The natural infections of untreated control samples led to a broad range of moulds. The rough visual inspection revealed *Aspergillus niger* and *Penicillium* species among others (Figure 3). All those infections were not observed on the acid-treated samples.

Not all species growing on the naturally-infected samples were identified. Each lingocellulosic substrate worldwide is accessible to mould growth, if it is not chemically or otherwise preserved or protected by wood accessory compounds, if moisture content is above fibre saturation and temperature above the freezing point.

All incubations were finally inspected after two months. There was still no mould growth on the acid-treated samples. Moisture content at incubation end reached from 7 to 16% with three exceptions above fibre saturation.

Prevention of rot

Freshly felled palm trunks with their high moisture content are susceptible to rot by wood-decay fungi. Already initial decay by brown-rot fungi can lead to reduced wood strength properties; for example, the compression strength decreased by 45% at only 10% mass loss (Liese and Stamer 1934; Pechmann and Schaile 1950). Unprotected palm wood becomes heavily degraded within few weeks of outdoor storage until a fibrous residue of vascular bundles.

Acetic and propionic acid do not belong to the traditional preservatives against wood rot fungi. To our knowledge, neither acetic acid nor propionic acid alone have been used to prevent rot from dicotyledonous woods. Palm wood samples were shortly dipped in solutions of acetic and propionic acid, respectively, and subjected to each one white-, brown- and soft rot fungus because only short-term protection of palm wood was intended. The effect of short dipping in maximum 10% solutions of both weak acids upon the cell wall components of the sample tissue is neglectable at room temperature; furthermore, the uptake of only 0.01-0.02 g acid/sample indicated that only the outer cells were impregnated by the chemicals.

Decay tests using mycelia of the Basidiomycetes *Pleurotus ostreatus* (white rot) and *Coniophora puteana* (brown rot) in malt agar Petri dishes (cf. Figure 1, right) showed that both Basidiomycetes colonized the untreated samples within three weeks, indicating the suitability of the test set-up. Growth of the soft-rot fungus *Chaetomium globosum* (Ascomycetes) was less visible, because those fungi mainly grow inside the substrate (Schmidt 2006).

Only few acid-treated samples were overgrown after three weeks. It was obvious that both acids prevented sample colonization when the mycelium got contact with the treated tissue. Although all samples had contact with their lower surface to the mycelium beneath, particularly the brown-rot fungus *C. puteana* colonized within eight weeks only five (date palm) and nine (oil palm) samples of the each 27 untreated controls (Table 3). Obviously, the presence of acid-treated samples near the control inhibited the fungus. Of the acid-treated samples, only one to five of each set of 27 samples were overgrown at the incubation end (Table 3). In contrast, the white-rot species *Pleurotus ostreatus* overgrew almost all controls (22 and 27) totally and from there stepwise the neighboured treated samples (Figure 3). A comparable effect was observed with Basidiomycetes when they grew on malt agar in the "ring-dish", a Petri dish containing separated areas of nutrient agar and poisoned agar: the mycelia started growth from the unpoisoned substrate and were the able to overgrow also the poisoned agar (Liese and Schmidt 1976). Such behaviour may be important for practice: if the fresh palm wood surface is not completely protected by acid, rot fungi may start growth from there and colonize also the treated wood.

Growth increment within a fungus and palm species combination was rather inhomogeneous, even after 8 weeks of incubation; some samples were only partly (5%) covered by mycelium, others were totally (100 %) overgrown (Figure 3). With regard to the different wood densities within a palm trunk, particularly in oil palm, there was a trend that the lighter palm wood samples were more affected; but there was no significant relationship between growth (and decay) and sample origin within the palm trunk. The retarded colonization of treated samples also occurred at the samples separated by a metal ring from the mycelium, which had been used to avoid a sudden contact of hyphae and acid.

The results of the decay test with each one white, brown and soft-rot fungus are shown in Table 3. Statistics were senseless due to the great variation in the time needed until sample colonization and in the percentage of sample overgrowth. Instead Table 3 summarizes for each fungus/palm/treatment the minimum, maximum and average (fat) mass loss and indicates the number of partly or fully overgrown samples for each combination. The small amount of chemicals (0.01-0.02 g acid/sample) taken up by dipping the samples was not considered for the calculation of the final mass loss.

Considerable decay of the untreated controls occurred by both Basidiomycetes within eight weeks of incubation (Table 3). The mass loss of the untreated date palm samples averaged to 25.7% by *P. ostreatus* and to 25.8% by *C. puteana*. The oil palm wood was more resistant with 12.7 % ML by *P. ostreatus* and 14.3% ML by *C. puteana*. Both acids substantially reduced the decay, but did not inhibit it totally. However, there were many samples within each set of 27 tested samples, which were neither infected by mycelium nor decayed despite infection. For example, only each one sample of the each 27 samples treated with 5 and 10% propionic acid was degraded by *C. puteana*.

The mass loss data for the soft-rot fungus *Ch. globosum* were rather low, however, also decreased by the influence of the acids. Probably, the test set-up on agar in Petri dishes was not suitable for the soft-rot fungus; the final moisture content of approx. 60% of the samples was below fibre saturation. Further studies may consider the standard ENV 807 (2001), which however needs longer incubation.

The main danger from propionic acid is chemical burns resulting from contact with the concentrated liquid. To protect applicators, protective clothing is necessary (Haque *et al.* 2009). As further disadvantage, the use of propionic acid is still limited because of its high cost and corrosive nature. With regard to the latter, its application by brushing or spraying is favoured above dipping which would need stainless steel containers.

In summary, the decay test indicated that the treatment of palm wood samples with acetic or propionic acid did not protect the wood absolutely against rot fungi, but inhibited infection during the first three weeks and reduced the decay considerably for at least two months.

Conclusion

Altogether, the laboratory investigation has clearly shown that palm wood can be protected from mould infection and severe decay by rot fungi for two months by a simple treatment with 5% solutions of either acetic or propionic acid. Further studies shall deal with larger samples to test if the technique also protects felled palm trunks at their cross-cut areas and sawn timber under practical conditions in their home countries during the critical time with high moisture content. It is assumed that repeated brushing or spraying of fresh cross-sections and other openings of the trunk as well of all fresh surfaces of sawn timber with an acid solution can prevent colonization by fungi until the wood has dried below fibre saturation either by air drying or kiln drying. To prevent rain on the treated surfaces the dipped or sprayed lumber must be stored under shelter to avoid washing-out of the acid. The trunk cross cut areas of felled trees should be protected repeatedly considering rain fall.

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Figure Legends

Figure 1. Experimental set-up. Left: plastic jar with acid-treated palm wood samples from different trunk areas and a Scots pine control (bottom) for mould test; right: Petri dish with malt agar overgrown by *Pleurotus ostreatus* mycelium and palm and beech wood (bottom) samples, from bottom clockwise: beech wood control, palm wood control, samples dipped in solution of 5 and 10% acetic acid as well as 5 and 10% propionic acid.

Figure 2. Naturally infection of untreated oil palm wood samples by air-borne moulds. Plastic jar with each three palm wood samples from bottom, middle and top part of the trunk. Within each part each one sample from inner, middle and outer trunk area. One Scots pine control.

Figure 3. Examples of growth of *Pleurotus ostreatus* on the control (at dish bottom) and acid-treated palm wood samples. In each Petri dish from bottom clockwise: control sample and samples dipped in solution of 5 and 10% acetic acid as well as 5 and 10% propionic acid.

Table 1. Fungi used.

Group	Fungus	Coding/origin
Moulds (Deuteromycota)	*Aspergillus niger*	Soil from pot-plant
	Penicillium sp.	"
	Cladosporium sp.	"
	Natural infection	Air-borne spores
White rot (Basidiomycota)	*Pleurotus ostreatus*	P11, ATCC 44737
Brown rot (Basidiomycota)	*Coniophora puteana*	P167, fruiting body, Hamburg 1997
Soft rot (Ascomycota)	*Chaetomium globosum*	P10, ATCC 44753

Table 2. Development of mould growth on untreated and acid-treated palm wood samples

Palm	Mould	Control			5% Acetic acid		5% Propionic acid		4% Boric acid	
		2 days	2 weeks	4 weeks	4 weeks*	8 weeks	4 weeks*	8 weeks	3 days	4 weeks
Date palm	*Aspergillus niger*	1	3	3	0	0	0	0	1-2	3
	Penicillium sp.	1	2-3	3	0	0	0	0	1-2	2
	Cladosporium sp.	0-1	0-3	2-3	0	0	0	0	0-1	3
	Natural infection	0	1-3	3	0	0	0	0	0-2	2-3
Oil palm	*Aspergillus niger*	1	3	3	0	0	0	0	1-2	3
	Penicillium sp.	0-1	3	3	0	0	0	0	0-2	2-3
	Cladosporium sp.	0-1	1-2	3	0	0	0	0	0-2	1-3
	Natural infection	0	1-2	3	0	0	0	0	0-1	3

0, no growth. 1, slight growth. 2, medium growth. 3, sample surface totally covered by mycelium and newly developed spores. *, second infection after 4 weeks of incubation.

Table 3. Decay (% mass loss) by rot fungi of control and acid-treated palm wood samples

Palm	Fungus	Control	Acetic acid		Propionic acid	
			5%	10%	5%	10%
Date palm	*Pleurotus*	10.7-42.0*	2.6-20.9	1.6-16.1	2.2-12.4	1.1-17.0
	ostreatus	**25.7****	**10.8**	**8.4**	**6.7**	**7.7**
		22***	18	18	13	12
	Coniophora	16.5-42.0	3.8-26.6	6.3-23.2	10.8-19.0	4.3-20.8
	puteana	**25.8**	**6.9**	**11.0**	**13.6**	**12.2**
		5	5	4	3	2
	Chaetomium	0.0-8.3	0.0-5.9	0.0-5.4	0.0-5.1	0.0-5.1
	globosum	**3.1**	**2.2**	**2.3**	**2.0**	**2.1**
Oil palm	*Pleurotus*	1.3-36.6	1.9-28.1	0.6-6.5	0.6-14.1	0.7-7.2
	ostreatus	**12.7**	**9.2**	**4.1**	**5.1**	**4.3**
		24	12	9	7	9
	Coniophora	1.1-37.0	3.8-17.0	1.4-9.3	11.2	1.4
	puteana	**14.3**	**8.3**	**5.4**		
		9	3	2	1	1
	Chaetomium	0.0-5.3	0.0-5.6	0.0-3.9	0.0-3.2	0.0-2.6
	globosum	**1.7**	**1.5**	**1.4**	**0.9**	**1.0**

*, minimum and maximum. **, average (fat). ***, number of overgrown samples of 27 tested samples.

Figure Legends

Figure 1. Experimental set-up. Left: plastic jar with acid-treated palm samples from different trunk areas and a Scots pine control (bottom) for mould test; right: Petri dish with malt agar overgrown by *Pleurotus ostreatus* mycelium and palm-wood and beech wood (bottom)

samples, from bottom clockwise: beech wood control, palm wood control, samples dipped in solution of 5 and 10% acetic acid as well as 5 and 10% propionic acid.

Figure 2. Naturally infection of untreated date palm wood samples by air-borne moulds. Each three samples from bottom, middle and top part of the trunk. Within each part each one sample from inner, middle and outer trunk area. One Scots pine control.

Figure 3. Examples of growth of *Pleurotus ostreatus* in Petri dishes on the control (at dish bottom) and acid-treated samples. In each dish from bottom clockwise: control sample and samples dipped in solution of 5 and 10% acetic acid as well as 5 and 10% propionic acid.

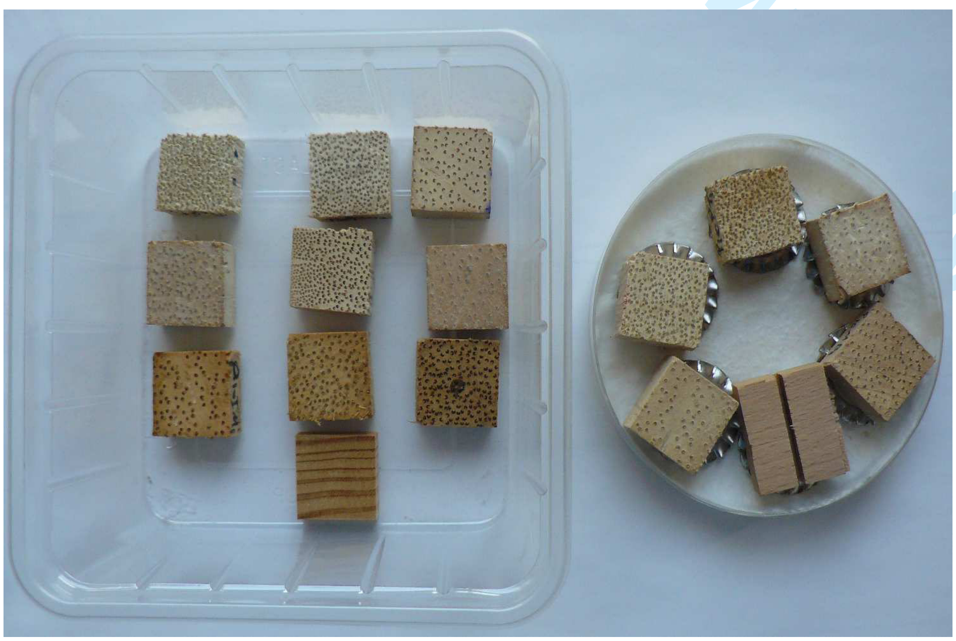

Figure 1.

Figure 2.

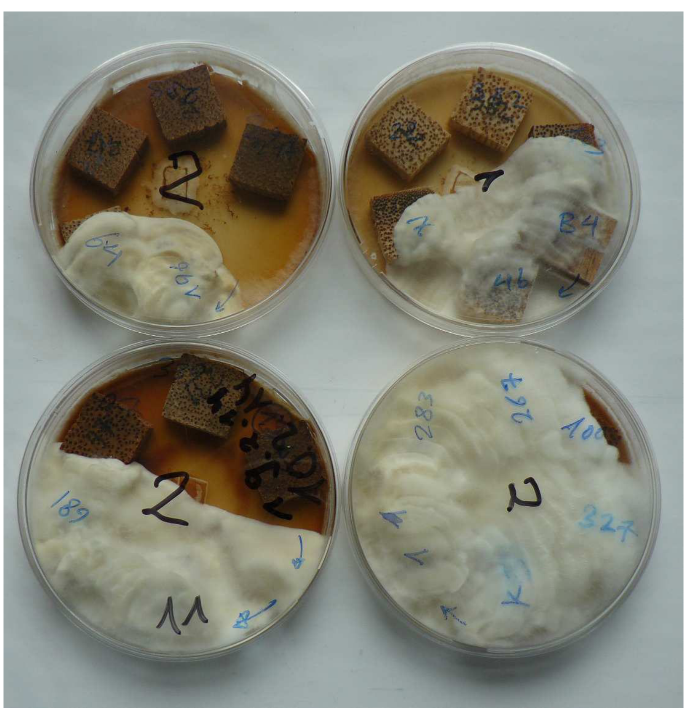

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Figure 3.

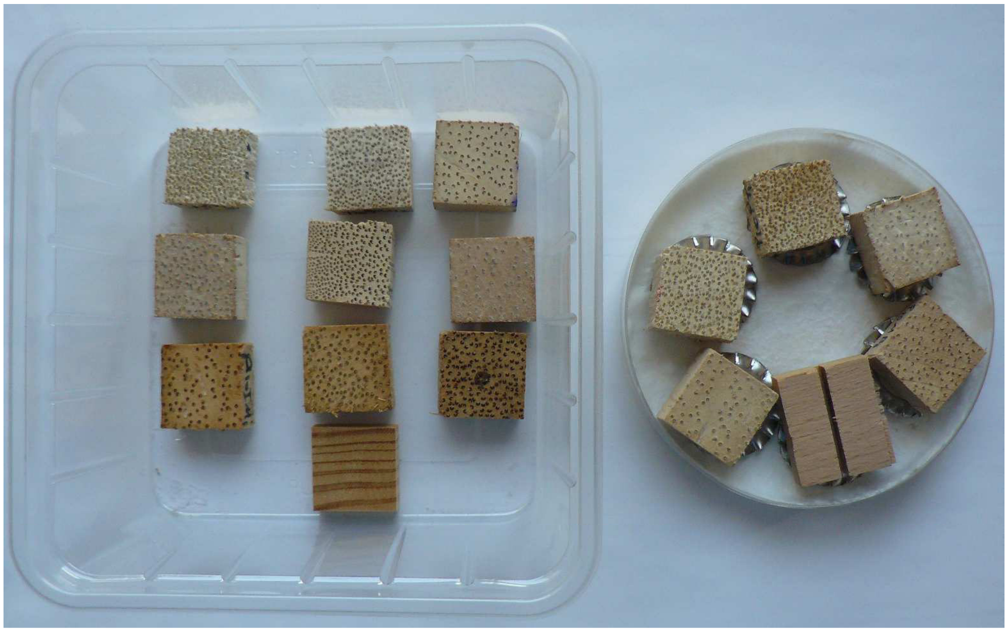


Figure 1. Experimental set-up. Left: plastic jar with acid-treated palm wood samples from different trunk areas and a Scots pine control (bottom) for mould test; right: Petri dish with malt agar overgrown by Pleurotus ostreatus mycelium and palm and beech wood (bottom) samples, from bottom clockwise: beech wood control, palm wood control, samples dipped in solution of 5 and 10% acetic acid as well as 5 and 10% propionic acid.
1050x655mm (72 x 72 DPI)

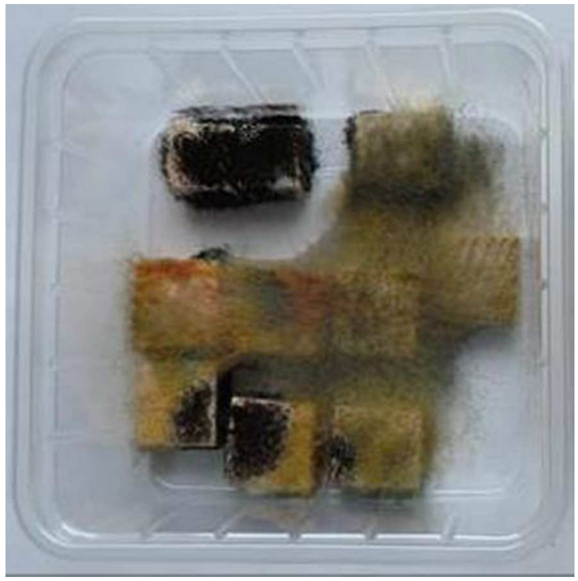


Figure 2. Naturally infection of untreated oil palm wood samples by air-borne moulds. Plastic jar with each three palm wood samples from bottom, middle and top part of the trunk. Within each part each one sample from inner, middle and outer trunk area. One Scots pine control.
75x75mm (96 x 96 DPI)

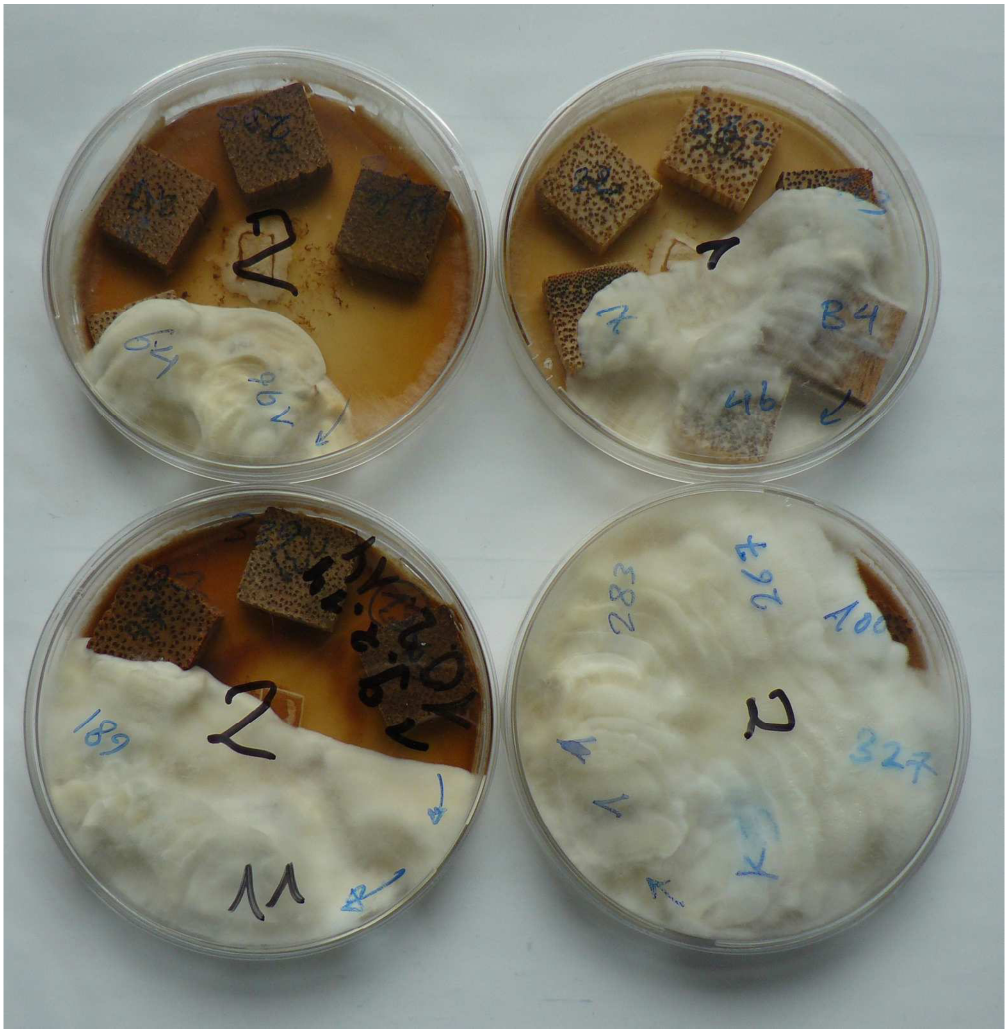


Figure 3. Examples of growth of Pleurotus ostreatus on the control (at dish bottom) and acid-treated palm wood samples. In each Petri dish from bottom clockwise: control sample and samples dipped in solution of 5 and 10% acetic acid as well as 5 and 10% propionic acid.
780x800mm (72 x 72 DPI)

67TH INTERNATIONAL CONVENTION

June 9-11, 2013 Austin, Texas

co-organizers

Forest Products Society

Society of Wood Science and Technology SWST

The Premier Event for Professionals in the Forest Products Industry

April 30, 2013

Dear Leila Fathi:

Thank you again for submitting a formal (oral) presentation for the Forest Products Society 67th International Convention, which will be held June 9-11, 2013 in Austin, Texas, USA. You will be speaking on your submitted abstract, **Structural and Mechanical Properties and Potential Uses of Coconut Palm Wood from Mexico**.

Please be sure to register for the conference before May 17, 2013 to receive the Early Bird rate and to guarantee your inclusion in the printed program. After May 17th, the price will be going up! You may start your registration here. **Note:** May 17th is a NEW, extended date for Early Bird registration.

Your speaker information packet is available for download. The packet will outline your responsibilities as a speaker as well as provide you with assistance when preparing and presenting your paper.

And finally, one of the most important aspects of this conference will be the production and distribution of the presentations. The *deadline for submission* of your full paper, extended abstract or PowerPoint presentation to be distributed via USB and made available at the conference is May 17, 2013. You may submit your file to Vicki Herian, Executive Director, Society of Wood Science and Technology at: Vicki@swst.org.

If you have any questions, please contact me at conferences@forestprod.org. We look forward to seeing you in Austin!

Sincerely on behalf of the Technical Committee and
Technical Chair, Niels de Hoop,

Megan C. Cuccia, CAE, IOM
Database Manager
Forest Products Society

First Name : LEILA
Last Name : FATHI
Passport Number: K17169667
Address: Leuschnerstr. 91 C , 21031 Hamburg, Germany

Tel: 004915212157615

Structural and Mechanical Properties and Potential Uses of Coconut Palm Wood from Mexico

Leila Fathi, Antonio Silva Guzmán, Raul Rodriguez and Arno Fruehwald

L. Fathi & A. Fruehwald
Department of Wood Science, University of Hamburg,
Leuschnerstraße 91, 21031 Hamburg, Germany
E-mail: leilafth@yahoo.com

J.A. Silva & R Rodriguez
Universidad de Guadalajara
Departamento de Madera, Celulosa y Papel.
e-mail: jasilva@dmcyp.cucei.udg.mx

Abstract

Wood from Palm Trees has not been used to a large extend but is an underestimated resource worldwide. According to FAO Oil-, Coconut- and Date palms cover some 30 million ha with a total potential stem wood potential of 100-200 million m³ per year. Generally this wood resource can play an important role in the regional/ worldwide wood supply. Being monocotyledons palms show distinct differences of the wood structure compared to common wood species. No radial growth of the stem and mainly consisting of parenchyma cells and vascular bundles result in distinct variation of density and mechanical properties.

In a comprehensive study based on Mexican coco-wood the relation of structure and mechanical properties is investigated. The research looks on number of vascular bundles, distribution across and along the stem, strength of the bundles, density, lignification and cell structure. Similar investigation is made with parenchyma. The aim of these basic studies is to develop a mechanical model in order to explain most mechanical properties from the density of the wood. This will lead to improved grading techniques of processed lumber. The wide variation and moisture content requires fast and good grading in order to improve industrial processing and general use.

Another part of the project deals with properties relevant for the use in various applications like the building sector (load bearing and decoration), furniture and handicrafts. These basic research findings with coco-wood can be used for other palm species as well in order to make use of the high resource potential.

Keywords: Palm wood, Coconut wood, vascular bundles, parenchyma, wood structure, mechanical properties.

8th Pacific Regional Wood Anatomy Conference

Annual Meeting of International Academy of Wood Science 2013

Nanjing Forestry University, Nanjing, P. R. China
Conference website: http://8th-prwac.njfu.edu.cn/index.asp
Conference office E-mail: prwac8th@163.com

August 28th, 2013

Subject: Invitation to attend the 8th Pacific Regional Wood Anatomy Conference & the Annual Meeting of International Academy of Wood Science 2013

Dear Leila Fathi,

We are pleased to inform you that the 8th Pacific Regional Wood Anatomy Conference (PRWAC 2013), combined with the Annual Meeting of International Academy of Wood Science 2013 (IAWS-2013) will take place in Nanjing, China, October 17-21, 2013. Your submission '**Relationship between structure and mechanical properties of coconut wood (*Cocos nucifera*)**' is accepted as oral presentation. I hope this invitation letter can help you to get visa. Please write us your airplane number and time after you fix it.

We are looking forward to meeting with you at Nanjing, China for this event.

Sincerely yours,

Qisheng Zhang, Professor
Chairman of 8th PRWAC and IAWS conference, 2013

Contact data of the organization in China

Address: Nanjing Forestry University, Longpan Road 159, Nanjing, 210037, Jiangsu.
Telephone: +86 25 85427550

Relationship between structure and mechanical properties of coconut wood *(Cocos nucifera)*

(Department of Wood Science, University of Hamburg, Hamburg/Germany) ○ **L. Fathi**
(Department of Wood Science, University of Hamburg, Hamburg/Germany) ○ **A. Frühwald**

Outline
A number of physical, mechanical and anatomical characteristics of coconut palm wood (CPW) originating from Mexico and Indonesia were investigated in order to evaluate inter-relationships of physical and echanical properties in relation to anatomical characteristics. In addition the wood properties tested on standardized samples the properties of the vascular bundles were investigated. More in detail, vascular bundles from different radial sections of the coconut palm trunk were examined for properties such as diameter, ultimate tensile strength and modulus of elasticity. The stress- strain diagrams have been determined. The influence of the vascular bundles on the overall properties of the wood is evaluated. These findings can be used for developing a mechanical model to describe coconut wood.

Keywords
Coconut wood, physical and mechanical properties, anatomical structure, vascular bundles

Introduction
Palm trees are a family of plants (Arecaceae). Palms are one of the most well-known and widely planted tree families. They have had an important role to humans throughout much of the history. Many common products and food come from palms, and they are also used a lot in parks and gardens. It is difficult to grow coconut trees in dry climate conditions. The stems are mainly converted into wood products in small scale operations - often in very rough form. The wood is difficult to machine because of density variations, high density and ash content. It is used as a substitute for conventional timber in building and bridge construction, but also for tools, toys, simple furniture, fencing and other items of daily life. In some parts of the tropics, e.g. the Maldives, coconut wood has been traditionally used for building fishing boats.

Results and discussion
The results indicated that density and compression behavior lengthwise are correlated to the anatomical characteristics like number of vascular bundles and their total area. All investigated mechanical properties, namely, compression strength parallel to grain, tensile strength (parallel and perpendicular to grain) and shear parallel to grain are increasing with distance from center to the peripheral part of the stem as well as with density and number of vascular bundles. The most important factors that influence strength properties are stem position and density. Because of the close correlation of physical and mechanical properties with stem position and vascular bundle number and total area, any one of these factors can contribute to the sorting of the timber into strength classes. Principally, the density decreases towards the center of the stem, and over stem height. Figure 1 gives a qualitative impression of the density distribution over the stem from five 80-year-old Philippine palms - Figure 2 shows the distribution of the vascular bundles and the density (dark = high density) over a cross section from Mexican coconut wood. The density ranges from low (0.41) to high (1.11 gcm^{-3}). The compression strength, tensile strength and shear strength also range from very weak to very strong due to the density variation. Generally the characteristics and properties obtained from the research were comparable with investigations on CPW from other parts of the world.

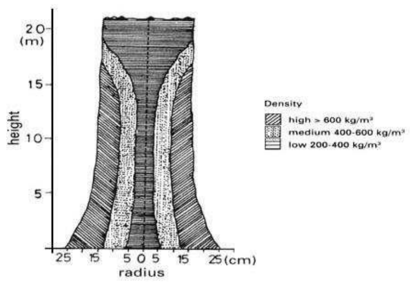


Fig. 1: Schematic density distribution in mature coconut palm stem (Killmann, W., Fink, D., 1996)

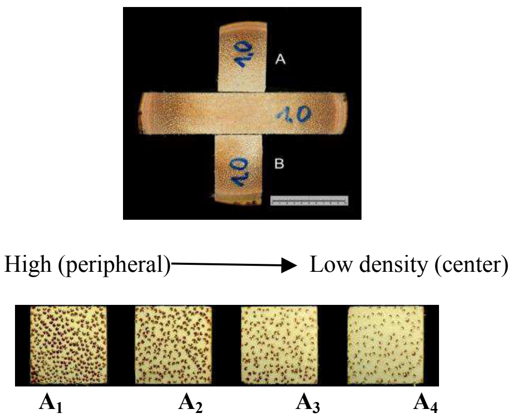


Figure 2: Cross section of coconut palm stem

May 8, 2014

Mrs. Leila Fathi
University of Hamburg
Leuschnerstrasse 91C
Hamburg, Hamburg 21031
GERMANY

Subject: Invitation letter
Passport number: **H95626773**
Date of birth: **16/09/1982**

Dear Mrs. Fathi:

From August 10 to 14, 2014, Québec City will host the **World Conference on Timber Engineering**. This meeting will be held at the Convention Center, in Québec City, from August 10 to 14, 2014.

According to the information received, we acknowledge your request for an arrival around **August 9, 2014** and a departure around **August 16, 2014.**

Please note that this letter does not imply any financial support related to your attendance, accommodation, travel, living expenses and/or any other expenses related to your stay in Canada.

For more information about the congress you can contact

Mrs. Mélissa Desrochers
Agora Communication
2600, boulevard Laurier, bureau 835
Québec (Québec) Canada G1V 4W2
wcte2014@agoracom.qc.ca

Hoping you will be able to join us in August 2014.

WCTE 2014 Organizing Committee

WCTE 2014 Quebec City Canada August 10-14
World Conference on Timber Engineering

THE POTENTIAL USE OF TIMBER FROM PALM TREES FOR BUILDING PURPOSES

Leila Fathi[1], Katja Fruehwald[2], Arno Fruehwald[3]

ABSTRACT: The harvesting volumes of tropical timber are declining. Several countries (i. e. in SE-Asia) have established plantations but only at a low level and with timber species having different (lower) properties. Palms play an important role in the tropical regions, as part of natural forests but even more as an agricultural crop. Coconut palms cover some 5 – 7 Mill. ha around all tropical regions and oil palms cover around 20 Mill. ha, of which 80 % are located in SE-Asia, mainly Indonesia, Malaysia and Thailand. It is estimated that in 2025 the area will exceed 30 Mill. ha. Due to the declining oil production, oil palms are replaced after 25 years. The trunk of the tree has on average a volume of 1.6 m³, which results in a total availability of oil palm trunks only in SE-Asia of 75 – 100 Mill. m³ per year at the present and more than 150 Mill. m³ per year after 2025.

There is no industrial processing and use of this resource yet due to the different structure and the properties of the wood and more difficult processing. Small quantities for building purposes and furniture are used locally.

The density of the wood varies significantly within the trunk as well as the moisture content. Mechanical properties are 20 – 30 % lower compared to common timber species as the wood contains higher amounts of ash, silica and sugar. But research has shown the possibilities of processing and manufacture of products, such as solid wood elements for construction, decoration, furniture, or packaging, plywood, and reconstituted panels. More recent research analyses the wood properties and the processing towards the manufacture of high quality products for the building and the furniture sectors. Glued timber products may be a key issue.

KEYWORDS: Coconut Palm, Oil Palm, Palm Timber, relation wood structure and properties, market potential palm timber

1 INTRODUCTION

Palms are a significant part of tropical forest and agricultural land use in the tropics. The two main species are coconut palms growing throughout tropical regions (total are ~5 – 8 million ha) and oil palms, mainly growing in South East Asia.

Oil palms are planted on large areas (Table 1); about half of the plantations are owned by small farmers, the other half by big plantation companies. Oil palms are planted to produce palm oil (production 4 – 5 t oil/(year·ha); value 3,200 – 4,000 US$). Nearing the age of 25 years of the tree, the oil production declines and the plantations are replanted. In fact, some 4 – 5 million ha plantations are over aged (> 25 years). The actual total area of oil palms of 20 million ha will increase until 2025 to about 30 million ha (or even more). This means that in addition to the overaged palm areas of 4 – 5 million ha presently, 500,000 ha/y have to be replanted. This figure will increase to about 1,000,000 ha/y after 2025.

Apart from the palm oil produced, the production of fibres is impressive. One palm tree produces in the period of 25 years, 0.28 t Empty Fruit Bunches (EFB), 1.8 t Oil Palm Fronds (OPF), 0.5 – 0.75 t (1.4 – 1.7 m³) Oil Palm Stems / Trunks (OPT), 0.5 t palm fibre and shells (total fibre 3.1 t) – all figures in dry matter. For comparison; the oil production is 0.8 t [1].

On the contrary to oil palms, coconut palms are planted on small areas only or as part of agroforestry systems. Most plantations are small and owned by small holders. The coconut palm reaches a height of about 15 – 25 m (trunk height 12 – 20 m, tall varieties) and has a mass of 0.6 –

[1] Leila Fathi, University of Hamburg, Leuschnerstr. 91, 21031 Hamburg, Germany. Email: leilafth@yahoo.com
[2] Katja Fruehwald, University of Applied Sciences Ostwestfalen-Lippe, Germany
[3] Arno Fruehwald, University of Hamburg, Germany and Palmwood R+D, Freiburg, Germany

0.85 t dry matter (1.1 – 1.4 m³). Aside from the trunks, the leaves (fronds) and the nut-shells (coconut fibres) are used.

As the new plantations with coconut are not established in larger quantities, the volume of coconut timber remains constant.

2 AVAILABILITY OF WOOD FROM TRUNKS AND PRESENT USES

2.1 COCONUT

The use of coconut fibre materials is well established:

– the coir from husks (nut shells) for mattresses, insulation material, and packaging,

– hard nut shells for charcoals and in milled condition, as glue extender,

– leaves and fronds for roofing, fencing, and simple frame wall construction,

– wood from trunk as building material (high densities for load bearing), interior decoration and furniture (medium and low densities).

The volume of trunks, which are processed mainly in sawn timber, is estimated to about 4 – 7 Mio. m³ per year worldwide (mainly in Asia and Central America). In the Philippines Coconut Wood is the wood number one in the building sector. The use is mostly local in small processing units. The potential is higher (~ 30 – 50 %) compared to the present utilization.

2.2 OIL PALM

The quantity of fibrous material is impressive, but currently the use is very small:

– EFB are used in Medium Density Fibreboard (MDF-) production (max 5 % of wood intake) and for energy,

– OP-fronds are tested for Medium Density Fibreboard (MDF) with little success and used for light buildings and for energy in small quantities,

– OP-trunks are not used at all in industrial or semi-industrial scale.

The availability of OP-trunks is already impressive and will get even more impressive:

130 - 150 palms per ha x 1.3 - 1.7 m³ per palm = 150 - 200 m³ per ha

current total: 500,000 ha x 150 - 200 m³ per ha = 75 - 100 million m³

total after 2025: 1,000,000 ha x 150 - 200 m³ per ha = 150 - 200 million m³

Considering the regional availability, the countries shown in Table 1 are dominating.

Table 1: *Regional Availability of Oil Palm Wood*

Indonesia	10 → 20 million ha (today → 2025)	→ ~ 40 → 100 mill m³
Malaysia	5 → 8 million ha	→ ~ 25 → 50 mill m³
Thailand	0.7 → 2 million ha	→ ~ 4 → 10 mill m³
others	4 → ? million ha	
total	20 → 30 million ha	→ ~ 85 → 200 mill m³

In comparison to the plantations in SE-Asia (oil palm, coconut palm, rubber wood, acacia mangium, and others), the availability of wood from the natural (tropical) forests is steadily declining (Table 2). Among all plantation species, oil palm timber has the highest potential by volume.

Table 2: *Availability of wood from natural forests and plantations (incl. palms, excl. bamboo) (source [2] and own estimates from interviews)*

	Ind. Roundwood trop. Forests [10^6 m³/y]			Roundwood from plantations [10^6 m³/y]	
	1990	2010	2020 estim.	2010	2025
Indonesia	100	15	10	45	100
Malaysia		19	20	40	80
Thailand		~ 0	~ 0	6	15

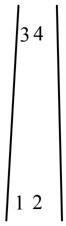
3 STRUCTURE AND PROPERTIES OF PALM TIMBER

Looking to the systematics of plants, palms belong to monocotyledons compared to “common tree species”, which belong to dicotyledons. For the latter, the stems grow in radial direction and get bigger in diameter (and height) with the time. The “growing tissue” cambium is all around the stem between wood and bark. Monocotyledons (like bamboo as well) grow only on the top of the plant/tree, where the “cambium” is located. No (primary) radial grow occurs. This is important for the structure of the “wood tissue”. In contrast to the “normal wood”, which has axial oriented cells (tracheids, fibres, vessels, parenchyma) and radial oriented wood rays, palms have no wood rays and lengthwise only parenchymatous ground tissue and vascular bundles (composed of vessels and fibres). Figure 1 shows the composition of palm wood.

Figure 1: Left: Cross cut section of palm wood with vascular bundles (darker dots) and parenchyma ground tissue. Right: Vascular bundles consisting of vessels and fibre caps (dark areas)

This structure results in a number of specific properties for palm wood in general:

- Parenchyma ground tissue cells have thin walls. According to cell lumen size and wall thickness, it can contain a lot of water (100 – 600 % mc) and "extractives", mainly sugar and starch (up to 8 %).
- Vascular bundles (VB), which consist of vessels for lengthwise water transport (from ground to cambium at the tree top), and fibres with thick walls arranged around the vessels for stability.
- Due to the lack of wood rays, palm wood is isotropic in radial/tangential direction but still anisotropic lengthwise/crosswise.
- The density of the VB is high between 0.8 to 1.4 g/cm³, while the parenchyma density is low from 0.1 to 0.6 g/cm³. The character of the wood is like a reinforced matrix system. This has consequences for the mechanical behaviour (see below) and for the processing (sawing, moulding, sanding) as the cutting forces push the hard VB into the matrix and after the spring back of the VB, the wood surface gets rough.
- The ash content of the wood is high (1.5 – 4.0 %) as well as the silica content (0.5 – 2.0 %) [3]. This is 3 to 5 (10) times higher compared to the "normal timber" species and causes rapid tool wear. Tungsten carbide or diamond tipped tools are a must.
- The high sugar and starch content favours (as long as the wood mc is above 20 – 25 %) the growth of mould and wood destroying fungi. The use of the wood in dry condition or the treatment with preservatives is required. After felling and during processing of the logs/lumber, temporary surface treatment is necessary. In Asia mainly borax/boric acid is used. Recently, it has been shown that organic acids are doing very well at low costs and minimum/no water/soil hazards [4].
- A major feature of palm timber is the distinct distribution of wood density in the trunk. Figure 2 shows the typical density distribution within the trunks of palms.



	average[1)] dry density [g/cm³]			
type of palm	1	2	3	4
coconut	0.80	0.40	0.60	0,25
oil	0.60	0.30	0.50	0.15
date	0.65	0.65	0.65	0.65

[1)] Density may vary +20/-30 % between trunks

***Table 3:** Density distribution in palm stems / trunks; 1, 3 near periphery; 2, 4 near inner axis of trunk*

- The distribution of the density within the trunk requires adopted/special processing technology (see chapter 4).
- The moisture content is high and varies between 50 – 100 % (areas of the highest densities) and 600 % (areas of the lowest densities). Wood drying is expensive and difficult in order to avoid drying defects, especially collapse [5].

4 CONVERTING LOGS INTO LUMBER FOR VARIOUS USES

According to the density distribution, the sawing pattern for the logs is different from normal patterns. Most experts recommend a pattern as shown in Figure 2 [6, 7]. In order to produce the lumber within certain density classes, it is necessary to know the density distribution within the log before sawing. Therefore roundwood density grading is required. No other quality grading for logs is necessary because the palm trunks are very straight (except coconut), uniform in diameter with a slope of ~ 0.5 cm per m, and they have no knots!

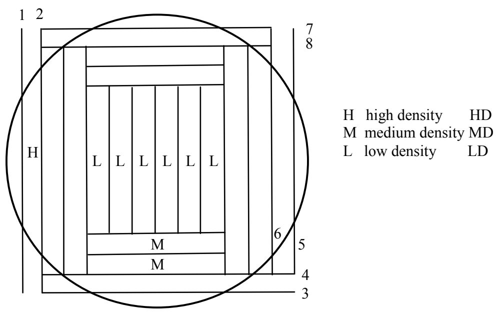


***Figure 2:** Typical sawing pattern for palm logs; 1…x sequences of cuts*

As density can vary within trunks and between trunks, a proper density (or strength) grading of the lumber is necessary after drying. Some experts even recommend the lumber density grading before drying to achieve the best drying results.

5 GRADING OF PALM LOGS AND LUMBER

Grading techniques for the palm timber should be able to grade wet and dry wood, roundwood, and lumber. Criteria for grading are density (dry, wet, roundwood, lumber) and strength (dry, lumber).

Well established methods for the grading of lumber are:

- Density calculation (mean value) from mass and volume
  - Possible with dry lumber, but needs accurate lumber dimensions and/or advanced volume measurement systems (laser).
  - Not possible with wet lumber, nor with moisture determination (accuracy), or for logs.
- Density measurement with γ- or X-rays (or similar)
  - Possible for dry lumber (high capacity of equipment), but not for wet lumber as the moisture determination is inaccurate.
  - Not possible for logs.
- Strength/Elasticity grading by deflection, ultrasonic or eigenfrequency
  - Possible for dry lumber.
  - Not possible for wet lumber or logs.
- Scanning technologies
  - Normally used for knots, cracks, fibre angle. Not required for palm timber.
- Determination of vascular bundles
  - Number and volume fraction are related to density and strength as VB are of high density and strength while parenchyma tissue has low density and strength. Theory and material property relationships are described in chapter 7.

6 PHYSICAL-MECHANICAL PROPERTIES OF PALM TIMBER

[8] tested mechanical properties of oil palm wood of different densities. The tested material was of lower density than the average densities from other studies. Table 4 shows the results, which are on the lower end because of the density.

Table 4: *Oil palm wood, density and some mechanical properties (figures re-calculated in N/mm²) [8]*

properties		zones across trunk diameter		
		peripheral	centre	inner
density [g/cm³]		0.40	0.20	0.18
bending [N/mm²]	MOR	41.7	18.5	8.4
	MOE	5,590	2,630	1,065
tension strength parallel to grain [N/mm²]		28.4	n.a.	n.a.
tension strength perpendicular to grain [N/mm²]		0.36	n.a.	n.a.
shear strength [N/mm²]		2.47	1.43	1.41

Table 5 gives an overview on typical densities, bending, and shear properties of timber from three palms compared to typical wood species used for timber construction.

Table 5: *Properties of palm timber and typical wood species used in timber construction (small, clear test specimens)*

Tree		density [g/cm³]	compression lengthwise (mean value) MOR [N/mm²]	compression lengthwise (mean value) MOE [N/mm²]	shear strength (N/mm²) (mean value)
Coconut Palm	MD	0.69	55	12,800	9.4
	HD	0.92	81	19,200	12.1
Oil Palm	MD	0.42	14	4,500	2.0
	HD	0.59	28	8,200	3.7
Date Palm	MD	0.67	15	4,300	1.5
	HD	0.72	21	7,500	1.5
Spruce [9]		0.47	60	9,500	6.5
Oak [9]		0.70	80	12,000	11.0
Pine [9]		0.52	85	10,500	8.0

Comparing the palm timber with Spruce, Pine, and Oak, it can be stated:

- Coconut timber (HD, MD) shows similar properties, but at 20 – 40 % higher density.
- Oil palm timber (HD, MD) shows only 25 – 35 % of the properties at lower or similar densities.
- Date palm timber varies only little in density but shows merely 25 % of the properties compared to common timber species.

At first glance, palm timber appears to have lower mechanical properties in the order of coconut > oil > date. Considering the fact that this comparison is made on the basis of small clear specimen tested, it should be noted that:

- Palm timber does not have knots and is almost uniform in the structure and the grain direction (very small slope of VB might occur). This means that the larger structural members might be very similar to the small specimen in regard to their properties.
- Almost all wood species can have knots with quite high slope of grain, which means that the structural members would have distinct lower strength properties (e. g. spruce average bending strength of small, clear, defect free test specimens is 78 N/mm² according to [9], however the characteristic bending strength of C24 softwoods is 24 N/mm² according to DIN EN 338:2013 [10]).

It is highly necessary to also test palm timber in full sizes; either as solid beams or as glued members. There is some likelihood that the differences in properties are smaller than the comparison in Table 3 suggests. For glued members, it is possible to distribute the single lamellas with different densities according to the stresses within the member.

7 A MORE DETAILED ANALYSIS OF THE MECHANICAL BEHAVIOUR OF PALM TIMBER

7.1 VB DISTRIBUTION WITHIN THE TRUNK

Figure 3 shows the typical pattern of VB distribution along the trunk radius (for coconut and oil palm; date palm might be different).

Peripheral Zone Center Zone of the stem

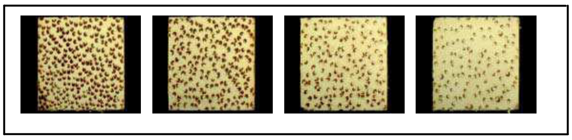


Figure 3: *Vascular bundle distribution along the trunk radius*

Table 6: *Number and volume fraction of VB in the wood of palms; p = peripheral, c = central, i = inner zone [11, 12]*

palm	section		number of VBs/400 mm²	share of VB on area [%]
coconut	bottom	p	288	44
		c	180	30
		i	109	13
	middle	p	n.a.	n.a
		c	n.a.	n.a.
		i	n.a.	n.a.
	top	p	364	n.a.
	[13]	c	n.a.	n.a.
		i	144	n.a.
oil	bottom	p	201	26
		c	121	16
		i	101	13
	middle	p	286	33
		c	166	21
		i	130	13
	top	p	332	31
		c	230	27
		i	163	16
date	bottom	p	213	33
		c	165	29
		i	155	24
	middle	p	300	30
		c	263	33
		i	244	25
	top	p	430	33
		c	333	33
		i	267	27

The vascular bundle diameter is generally between 0.5 and 0.9 mm (with some exceptions). Number of VB is between 25 and 85 VB/100 cm² for oil palm. Table 6 gives some data on the share of VB of the wood.

The density of VB is between 0.8 and 1.4 g/cm³. Knowing the volume fraction and the density of VB, it is possible to calculate the density of parenchyma. The density of VB and of parenchyma tissue is getting higher by the "secondary growth", which means that more cell wall layers are added on the cell wall towards the lumen of the cells. This happens with the time resulting in the higher densities at the bottom of the trunk. This can have a high influence on the strength / elastic behaviour since the low density wood is characterised by the lower volume fraction of VB (due to number and diameter), the lower density of VB (younger cells), but even much lower density in the parenchyma.

The parenchyma density influences the shear properties dominantly.

7.2 STRENGTH PROPERTIES OF VASCULAR BUNDLES

[12] tested the tension MOR and MOE of single vascular bundles and observed much higher values compared to the wood itself (Table 7).

Table 7: *Values for MOR and MOE of single vascular bundles, average for samples graded as log density and high density (LD / HD)*

	min…max values for	
	MOR [N/mm²]	MOE [N/mm²]
oil palm	160…220	11,000…17,000
coconut palm	230…250	18,000…25,000

These values are remarkably higher compared to MOR and MOE for wood. [8] found the tension strength for the wood from the peripheral trunk zone of oil palms to be between 7 and 40 N/mm² depending on the tree height. If, for example, the peripheral zone at the trunk base is considered, the MOR is 40 N/mm² [8]. However, if it is calculated from MOR of VB and 30 % volume fraction of VB of the wood, a "theoretical MOR for the wood" is 0.3 x 220 = 66 N/mm². [12] gives more examples for this kind of modelling. It can be stated that the biggest share on MOR in tension (and other loading) by far is from the contribution of vascular bundles.

The high MOE and MOR of the VB and the much lower properties of the parenchyma as ground tissue, especially the shear behaviour, are the typical "problems" of reinforced materials. It has been observed with tension test that the failure type is a mix of tension failure of the VB and a shear failure in the parenchyma. This means that the tension stress is unevenly distributed over the test area if the test specimen is not well designed. Similar problems occur in tests for compression parallel: the VB are buckling because the parenchyma is "weak" across the fibre (very thin walls).

7.3 CONSEQUENCES FOR THE USE UNDER LOAD

Presently the knowledge of the mechanical behaviour of palm wood is quite small. A lot of research is needed to fully understand palm timber and to define design values. But as the potential concerning volumes is high and the material is quite uniform (except density distribution), the technical potential is high. Tests have shown that the gluability of palm wood is without major problems [7, 3, 14]. The use of timber with various densities within one structural member seems possible.

7.4 CONSEQUENCES FOR GRADING

It is obvious that the number and the share / volume fraction of VB is influencing the density and the mechanical properties. [12] found, for example, the statistical coefficients of correlation in Table 8.

Table 8: *Coefficients of correlation (R^2) between different material properties of oil palm timber*

proper-ties	trunk height	Bottom of top resp.				
		loca-tion in trunk	den-sity	MOR II compr.	num-ber of VBs	share of VB
density	bottom	0.95		0.98	0.96	0.97
	top	0.29		0.35	0.27	0.39
MOR II compr.	bottom	0.92	0.98		0.96	0.97
	top	0.86	0.35		0.96	0.07
number of VBs	bottom	0.88	0.96	0.96		0.95
	top	0.95	0.27	0.96		0.12
share of VB	bottom	0.92	0.97	0.97	0.95	
	top	0.16	0.39	0.07	0.12	

Although the tests made by [12] included a limited amount of test samples, it seems possible that number and share / area and volume fraction of VB can be used as indicators for density and strength grading. This requires appropriate scanning technique, more detailed testing, and establishment of relationships. This principle might be possible to use for dry and wet lumber as well as for logs to determine the sawing patterns.

8 POTENTIAL TIMBER PRODUCTS

Since around 1985, tests were made to use wood from oil palm trunks. Bases have been the knowledge of converting coconut timber into timber based products (examples given in [6]). But as the density of coconut is significantly higher compared to oil palm and it contains also less sugars (which results in better natural durability), the spectrum of products for oil palm timber may be different from coconut timber. Coconut timber is used as high density (HD) material for load bearing construction, whereas MD and LD material is used for flooring, wall panelling, furniture, packaging, and insulation material.

For oil palm wood an early overview is given by [15]. They are describing laboratory-based production and testing of sawn timber, block boards, particle board, Medium Density Fiberboard, plywood, pulp, and paper.

More recently, block board with oil palm core and furniture stock and door frames have appeared on the market (Palmwood Technology Malaysia). Oriented Strand Board [16] as well as some other products for interior use have been tested.

A general potential for products is seen in the following product lines:

A solid based lumber
construction timber solid and glued
gluelam
moulded lumber for use in buildings
furniture, furniture components
packaging, transport

B solid wood panels
single layer glued solid panels
three layer / multi-layer solid panels (CLT)
block boards
flash doors (core, framing)
multi-layer flooring elements

C reconstituted panels
Medium Density Fibreboard (MDF)
particle board (PB)
oriented structural board (OSB)
continuous strand lumber (CSL)

D plywood
flat plywood
2D – 3D plywood
Laminated Veneer Lumber (LVL)

9 CONCLUSIONS

Oil palm wood availability provides good opportunities of supplementing / substituting common tropical timber species especially in Asia. As the oil palm wood (similar to other palms) is different in the structure and the properties compared to common timber species, product development and process development is a necessity for achieving market competitiveness.

There is a need to increase the research efforts for both product development and process development. Market studies and marketing activities could speed up market acceptance and market penetration. For load bearing products, long term durability under load (and wet climate) as design values as well as standardization (matching with building codes) are significant challenges.

For oil palm wood utilization, two new strategic initiatives have been initiated recently for the R + D, commercialization, and promotion. A network on R + D is being established in Asia and Europe (more information will be given soon under palmwood.de) and a network for commercialization is also being under way (more information soon under PalmwoodNet.com).

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Declaration

In line with the regulations on dissertations of the Department of Biology, University of Hamburg I hereby declare that I have done the present work by myself, not used other than the sated sources and aids, that any used statement from literature is noted and that I have listed all third party help.

Leila Fathi