Physical-Mechanical Properties and Natural Durability of Lesser Used Wood Species from Mozambique

Alexandre Charifo Ali
Faculty of Forest Sciences
Department of Forest Products
Uppsala

Doctoral Thesis
Swedish University of Agricultural Sciences
Uppsala 2011

Acta Universitatis agriculturae Sueciae
2011:32

ISSN 1652-6880
ISBN 978-91-576-7567-5
© 2011 Alexandre Charifo Ali, Uppsala
Print: SLU Service/Repro, Uppsala 2011

Physical-Mechanical Properties and Natural Durability of Lesser Used Wood Species from Mozambique

Abstract

The aim of this study is to assess properties of lesser used/known timbers from Mozambique. The studied species were ncurri (*Icuria dunensis* Wieringa), ntholo (*Pseudolachnostylis maprounaefolia* Pax), metil (*Sterculia appendiculata* K. Schum), namuno (*Acacia nigrescens* Oliv.) and muanga (*Pericopsis angolensis* Meeuwen).

A comprehensive literature review found the Mozambique timber sector to be dominated by very few hardwood species while the rest of 118 lesser used wood species are almost unexplored. The above mentioned lesser used timbers were selected and subjected to descriptive and comparative analyses aiming at describing the physical-mechanical properties and natural durability with regard to prospective end uses.

Standard test methods determined density, moisture content, dimensional stability characteristics, colour, natural durability and a number of mechanical properties of the selected lesser used timbers. The study revealed that ntholo and ncurri are heavy timbers with a density in the range of 850-1100 kg/m^3 and very low dimensional changes. Metil is a medium light wood with an average density of 550 kg/m^3 at 12% moisture content and a coefficient of anisotropy of 1.8 from green to oven-dry state. End use assessments suggest that the timbers of ntholo, muanga and namuno can be used in similar applications as the well known timbers, e.g. internal joineries, tool handles and furniture. Metil timber seems suitable for packaging boxes, plywood and construction purposes. In terms of natural durability, the results showed that heartwood of namuno, muanga and ntholo can be classified as very durable to deterioration and degradation caused by fungi and termites. These timbers showed good performance when untreated samples were exposed in- and above ground field tests providing a good indication of the expected service life and outdoor use features. Wood of metil was classified as non durable to any of the considered hazards and is not recommended for exterior uses unless treated with appropriate wood preservatives.

The study determined ntholo timber mechanical properties and examined interrelationships with density and anatomical features of ntholo through regression and correlation analyses. The study found ntholo to be a very dense timber with high mechanical strength in comparison to well known timbers. The regression analyses show that both ntholo sapwood and heartwood densities are poor predictors for the tested mechanical properties, although may provide some indication of tested properties.

All tested properties of ntholo sapwood were influenced mainly by ground tissue proportions, while heartwood properties were described by more leveled anatomical predictors. Fiber length was the only anatomical feature significantly correlated to density and all tested mechanical properties of ntholo. The number of vessels/mm^2 and % vessels were not significantly correlated to any of the measured properties but appeared to be key anatomical features for predictions under regression analysis.

The integrated analysis of results from this study is expected to form a reliable background for a successful utilization of the relatively lesser explored timbers from Mozambique.

Keywords: Lesser used timbers, mechanical properties, Mozambique, natural durability, physical properties

Author's address: Alexandre Charifo Ali, SLU, Department of Forest Products,
P.O. Box 7008, 750 07 Uppsala, Sweden
E-mail: alexandre.charifo.ali@slu.se

Dedication

To the memory of my father Charifo Corirriwa

Contents

List of publications

The present thesis is based on the following papers, which are referred to by their Roman numerals:

I. Ali, A. C., Uetimane Jr, E., Lhate, I. A. and Terziev, N. (2008). Anatomical characteristics, properties and use of traditionally used and lesser known wood species from Mozambique: a literature review. Wood Science and Technology 42:453–472.

II. Ali, A. C., Chirkova, J., Terziev, N. And Elowson, T. (2010). Physical properties of two tropical wood species from Mozambique. Wood Material Science and Engineering 5 (3):151–161.

III. Ali, A. C., and Uetimane Jr., E. (2010) Physical and mechanical properties of metil (*Sterculia appendiculata* K. Schum), a lesser used timber species from Mozambique. In Wood Structure and Properties. Edited by Kúdela, J. and Lagana, R. Arbora Publishers, Zvolen, Slovakia, pp. 149–154.

IV. Uetimane Jr, E. and Ali, A. C. (2010). Relationship between mechanical properties of ntholo (*Pseudolachnostylis maprounaefolia* Pax) and selected anatomical features. Journal of Tropical Forest Science (*in press*).

V. Ali, A. C., Uetimane Jr., E., Råberg, U. and Terziev, N. (2010) Comparative natural durability of five wood species from Mozambique. International Biodeterioration & Biodegradation (*in press*).

Papers I – III are reproduced with the kind permission of the publishers.

Abbreviations

CEN	European Committee for Standardization
CIE	Commission International de l'Eclairage
COPANT	Comision Panamericana de Normas Tecnicas
DNFFB	Direção Nacional de Florestas e Fauna Bravia
DNTF	Direção Nacional de Terras e Florestas
EN	European standards
ENV	European environmental standards
GDR	Gross domestic product
ISO	International Organization for Standardization
MAE	Ministério de Administração Estatal
prENV	European environmental prestandards

1 Introduction

1.1 Background

Forests in Mozambique consist of miombo woodlands, tropical rain forests and savannas. They cover 78% of the land surface of the country and represent an important part of the ecology (Bandeira et al. 1994). The forests provide diverse benefits to the local people, including material for constructions, firewood and charcoal production. The forests constitute one of the major sectors in the country's economy. In recent years the contribution of forest exports and wood industry to the gross domestic product (GDR) was on average 3% (Alberto 2006).

Nowadays, the stock of well-known wood species such as chanfuta (*Afzelia quanzensis* Welw), jambirre (*Milletia stuhlmannii* Taub) and umbila (*Pterocarpus angolensis* DC) has become scarce in Mozambican natural forests. As an illustration, chanfuta, jambirre, and umbila were the main commercially used timbers, comprising respectively 19, 30 and 30% of total volume, i.e. the three species represented 79% of total exploited wood in Mozambique in 2004. However, the total commercial volume of timber of the same species fell to 54% in 2005 because their availability has rapidly declined in natural Mozambican forests (DNTF 2006). In this context, the harvesting of abundant but lesser used wood species needs to be gradually encouraged and increased in Mozambique. Hence, the use of a broader range of species will conform to what the natural forests can produce sustainably to the demand and also will contribute to reduce the depletion of well-known wood species (Barany et al. 2003).

Modern forest management approaches which include the search for alternative substitute timber species for those most exploited are increasingly employed in the timber sectors in Africa. Remarkable progresses were reported from Ghana (Otengo-Amoako 2006) and Tanzania (Gillah et al. 2007). Several studies about wood properties of lesser used species growing in Africa aiming to reduce pressure on the well known species have been conducted (Poku et al. 2001; Ishengoma et al. 2004; Zziwa et al. 2006).

In the present study, five lesser used wood species from Mozambique were studied, namely metil (*Sterculia appendiculata* K. Schum), ntholo (*Pseudolachnostylis maprounaefolia* Pax), muanga (*Pericopsis angolensis* Meeuwen) namuno (*Acacia nigrescens* Oliv.) and ncurri (*Icuria dunensis* Wieringa). The selection of metil, ntholo, muanga and namuno was based on the fact that a recent forest inventory conducted in the country reported abundance of their volumes. Their growing stocks were estimated as 6.5 million m^3 for metil, 4.1 million m^3 for ntholo, 1.9 million m^3 for muanga and 2.4 million m^3 for namuno (Marzoli 2007). Ncurri is rapidly growing but still endemic species used by local population and is confined to a stretch of about 200 km in the northern coast of Mozambique (Wieringa 1999). Due to its protected status, ncurri timber is not aimed for export and intensive industrial use, but the species was included in the study to provide additional information that may be important for its characterization including accurate identification.

Wood anatomy studies for some of the above mentioned timbers have been previously published, e.g. ncurri (Wieringa 1999), ntholo, metil and muanga (Uetimane et al. 2009). The drying behaviour of ntholo has also been recently examined by Uetimane et al. (2010). Very initial studies in West Africa included some with physical and mechanical properties of namuno (Lemmens 2006) and muanga (Lumbile and Oagile 2008). However, the wood natural durability of all the above mentioned lesser used wood species has never been studied.

Ishengoma et al. (2004) highlights the importance of knowledge of wood properties of lesser used timber species prior to their market promotion. Thus, the present study is devoted to determine the principal physical and mechanical properties together with natural durability of some lesser used timber species from Mozambique. The specific objectives are given in Section 1.4.

1.2 Unity of wood properties

Wood is a unique material in which the chemical composition, anatomical features, physical, mechanical properties and natural durability are interrelated. This has been confirmed by a great number of studies of which the recent ones by Winandy (1994), Simpson and TenWolde (1999) and Chowdhury et al. (2007) are good examples of the unity and interrelations of the properties. Wood physical properties are referred as quantitative characteristics of wood and its behaviour to external influences rather than applied forces (Winandy 1994). The most studied physical properties for determining the wood end uses comprise density, wood-water relations, shrinkage, swelling and colour (Siau 1979; Simpson and TenWolde 1999; Bowyer et al. 2003).

Density of wood is probably the most descriptive of all properties. The main structural compounds, i.e. cellulose, hemicelluloses and lignin have similar densities thus, any combination of these compounds leads to an approximate density of 1.53 g/cm^3 (Kollmann and Côté 1984) of the cell wall substance regardless wood species. With this in mind when measuring the density of wood, we can easily calculate the part of volume occupied by only wood substance or *porosity* of wood. Apparently the rest of the volume can be occupied by water. The practical importance of the above can be illustrated by calculations on the maximum amount of protective water based formulations that can be impregnated in wood of permeable species. Such calculation fits perfectly the sapwood of Scots pine but is not applicable to wood species with low permeability caused by limited number of opened pits (e.g. in Norway spruce) and/or extractives located in the cell lumens (e.g. ntholo and other tropical timbers). Since wood density is interrelated to the amount of water, four densities (raw, density at 12% MC, density at absolute dry weight and basic density) are used worldwide. Wood density is undoubtedly an important timber property as it influences the yield and quality of solid wood products and wood-based composites (Alteyrac et al. 2006; Gryc and Horácek 2007). Density and porosity influence the thermal conductivity and diffusivity of wood (Suleiman et al. 2006) as well as acoustical properties (Chauhan and Walker 2006).

Moisture in wood is found as water vapour, free water in the cell lumens and cavities and as bound water within the cell walls (Siau 1979; Choong and Achmadi 1991). The moisture content (MC) at which the cell walls are fully saturated with bound water but no free water occurs in the structure is designated as fibre saturation point (FSP). As already discussed, the amount of free water depends on porosity while the amount of bound water is related to the free hydroxyl groups of the main structural compounds that can attract water molecules by electro-static forces. Although the ratio between the main structural compounds varies, the maximum amount of bound water in wood of various species changes in a narrow interval of 25-30%. The FSP of Scots pine is similar to that of ntholo and ncurri although these species are soft- and hardwoods respectively. The MC of wood below the FSP is a function of temperature and relative humidity (RH) of surrounding environment. The equilibrium moisture content (EMC) is defined as the MC at which wood neither gains nor loses moisture (Choong and Achmadi 1991). Electrical conductivity of wood is another property that depends on the amount of water present.

Variations in RH force wood to accept or release water molecules leading to dimensional changes when the wood MC is below the FSP.

Shrinkage occurs when wood loses moisture from cell walls, while *swelling* takes place when it gains water (Bowyer et al. 2003; Hernandez 2007). As an anisotropic material, wood shrinks and swells most in the tangential direction, about half as much across the radial direction and insignificantly along the longitudinal direction (Kollmann and Côté 1984; Simpson and TenWolde 1999). The combined effects of radial and tangential shrinkage can distort the shape of a wood piece. Shrinkage and swelling can also contribute to checks, warping, splitting and overall performance problems that make wood products less useful (Winandy 1994). The dimensional changes of wood are related to the chemical composition and extractive content but also to fibre morphology and tissue proportions.

Wood density and moisture determine to a great extent the *mechanical properties* of wood including elastic properties which characterize resistance to deformation and strength properties that characterize resistance to applied loads. In general, density explains from 60 to 98% of variations when modelling modulus of rupture and elasticity, compression strength and even hardness in softwoods (Tsoumis 1991). As shown in **Paper IV**, the relationship between density and strength can be weak for some hardwoods, e.g. ntholo. Moisture below FSP strongly influences the mechanical properties (Stamm 1964). Strength used to be presented in terms of stress, i.e. force per unity area and strain or deformation caused by the applied stress. According to the literature, the most commonly determined mechanical properties are modulus of rupture (MOR) in static bending, maximum stress in compression parallel to grain, shear strength parallel to grain and compressive stress perpendicular to grain.

Outdoor utilisation of wood is limited due to its susceptibility to biodegradation. The inherent ability of wood species to resist biological deterioration is referred as *natural durability* or decay resistance (Eaton and Hale 1993; Johnson et al. 2006). The principal biological agents that degrade wood are bacteria, fungi, insects, e.g. termites and beetles, and marine borers (Tsunoda 1990; Highley 1999). Natural durability varies between wood species and is explained mainly by the composition and amount of wood extractives. Extractive deposits formed during the conversion of sapwood to heartwood often make the heartwood of some species more durable since generally higher heartwood extractive content imparts higher decay resistance of wood species (Onuorah 2000; Pometti et al. 2010). Lignin content adds to the natural durability, e.g. birch vs. pine. Knowledge about natural durability is obtained by field and laboratory tests as well as by practical experience of the end users (Willeitner and Peek 1997; Gierlinger et al. 2003).

Moisture has great impact on wood durability and service life because it is a prerequisite of vital importance for the wood destroying organisms.

Although studied intensively, no clear relationship between wood density and natural durability has been found (Boutelje and Nilsson 1985). On the other hand, the most realistic description of microbiological deterioration is the monitoring of density changes by weight loss and decrease of some strength characteristics, e.g. modulus of elasticity and compression strength. The unity of density, strength and wood durability is even standardised (e.g. EN 113 and EN 252) to give a comprehensive description of wood behaviour.

Papers IV and **V** could be regarded as examples of the unity of anatomical, physical, mechanical properties and durability of wood. Uetimane et al. (2009) reported that the average vessel lumen diameter was 371 μm in metil, while in ntholo and muanga these dimensions were on average 108 and 131 μm respectively. The large void volume of metil explains its low density and poor mechanical properties while its low durability compared to the other two species is explained by the extractive content in metil lower than 3% while that in ntholo and muanga is higher than 7% (Lhate et al. 2010). Wide vessels and lack of extractives provides metil's high permeability and consequently, easy moisture uptake. The susceptibility to biodegradation of metil wood is significantly higher when compared to the other four species as demonstrated in **Paper V**.

1.3 Limitations of study

Trees are living organisms with a great variability in structure and properties. The variability exists as inter- and intra-tree variation and also between growing stands. The environmental conditions are also one important source of wood anatomical structure variability which influences the physical and mechanical properties. Genetic features (species and genus), environmental factors, including soil, climatic conditions and other physiological effects, operate simultaneously, influencing the character and organisation of individual anatomical elements (Gryc and Horácek 2007). Nevertheless, the samples used in this study were collected in a way that each species was taken from a single stand due to technical and economical reasons. Thus, the samples do not cover all potential ranges of variability. The number of trees sampled for each species was limited to 5, i.e. the minimum permissible according to standards.

The age of the trees collected for this study is unknown, because the sampling process took place in natural tropical forests. A simple method for determining the age of trees is counting their annual rings or coloured layers. However this method is usually limited to trees of which accurate information about the date of planting is available, such as in the cases of plantations and botanical gardens (Worbes 1995; Verheyden et al. 2004). In the case of this study, the use of counting annual rings method was not practical because the annual rings were not easily distinguishable. The specimens for mechanical tests were taken in a way to avoid juvenile wood.

It is common that in many wood species the heartwood may contain deposits of extractives that frequently give the heartwood a much darker colour than sapwood. This does not occur in metil where both heart- and sapwood are identical in colour. Thus, the studies on metil properties were not conducted using separate heart- and sapwood.

This work studied and discussed only some of physical properties most relevant to wood processing, structural design and potential end use selection, including density, moisture content, dimensional stability and colour. The study on the relationship between wood anatomy, density and mechanical properties, the number of specimens in each set was limited to 20 because the anatomical analyses were very laborious and time consuming.

Although the timber was carefully packed and sealed, the wood moisture content has probably decreased during the 2-week long transportation from Mozambique to Sweden. This means that the green moisture content values presented in this work might appear slightly lower than those that would be found if the measurements were carried out immediately after cutting.

Trials concerning natural durability of wood were not carried out for sapwood of muanga because its thickness was less than 1 cm. The durability test with basidiomycete fungi was limited to four fungi.

1.4 Objectives

The main objective of this study was to provide an initial but reliable database of physical-mechanical properties and natural durability of the studied species and tentatively suggest potential end uses of the lesser used timbers based on their physical, mechanical and decay resistance properties. This is achieved by:

1. Review on the timber sector in Mozambique and discussion on the research needs concerning the lesser used wood species in the country;
2. Study and presentation of fundamental physical and mechanical properties of ncurri, ntholo and metil with regard to eventual end uses. Assessment of natural durability of ncurri, ntholo, metil, muanga and namuno;

3. Study and model covering the relationship between wood anatomical characteristics, density and mechanical properties of ntholo through a combined and complementary approach of correlation analysis and simple and multiple regression analysis. Investigations on the predictability of mechanical properties from wood anatomical features and density.

2 Material and methods

2.1 Timber sector in Mozambique

This part of the study comprised gathering and analysing timber species fact sheets, official documents and reports from the Ministry of Agriculture to survey the timber sector in the country.

2.2 Studied species and sampling

The wood species studied are listed in Table 1.

Table 1 – Studied wood species

Scientific name	Vernacular name	Family
Acacia nigrescens Oliv.	Namuno	*Leguminosae-Mimosoideae*
Icuria dunensis Wieringa	Ncurri	*Leguminosae-Caesalpinioideae*
Pericopsis angolensis Meeuwen	Muanga	*Leguminosae-Papilionoideae*
Pseudolachnostylis maprounaefolia Pax	Ntholo	*Euphorbiaceae*
Sterculia appendiculata K. Schum	Metil	*Sterculiaceae*

Five trees of each species were sampled according to COPANT (1972) standards and also according to the least diameter at breast height (DBH) over bark for harvesting, recommended by DNFFB (2002) for those species. The trees were felled at approximately 15 cm above ground. The location and climate of sampling sites in Mozambique, the tree growth conditions and sampling procedures are detailed in the **Papers II** and **V**.

The climate of the sampling sites is typical for northern Mozambique and is characterized as subtropical, with alternating cool and dry winters, lasting from April to September and hot and rainy summers from October to

March. The average annual precipitation ranges from 800 to 1000 mm and average annual temperature from 20 to 26 °C (MAE 2005a; MAE 2005b).

2.3 Physical properties

2.3.1 Preparation of test specimens and experiments

Five trees of each of the studied species were felled and cut to three logs except ncurri trees which were cut to only two logs. The logs were sawn to 50-mm-thick radial planks which were packed in plastic bags. After approximately 2 weeks of transportation the timber was stored in a refrigerator at -20 °C. Specimens for determination of the physical-mechanical properties were prepared from the radial planks obtained from each log and tree. The planks were sawn, planed and specimens strictly oriented in radial/tangential direction were cut from pith to outer part of the bole (adjacent to bark).

Sampling methods, numbers of samples and general requirements for physical tests have been followed throughout the study. International Organization for Standardization (ISO), in particular ISO 3129 (1975) was used as the leading standard. The specimens were labelled in a way that the identification of their positions in the tree and log could be traced.

Laboratory experiments on physical properties were conducted according to the ISO standards. Density, green MC, shrinkage and swelling (longitudinal, tangential, radial and volumetric) were determined according to ISO standards 3130 (1975), 3131 (1975), 4469 (1981), 4858 (1982), 4459 (1982) and 4460 (1982). The procedures for determining the above wood properties are detailed in **Paper II**.

2.3.2 Water vapour sorption determination

Water vapour sorption-desorption isotherms were measured and used to determine the FSPs and characterize the wood-water relations in the cell wall for only ncurri and ntholo. The isotherms were measured on a vacuum sorption balance with quartz spirals at temperature of 22±0.1 °C and residual pressure of 1 Pa. The mass of the sample was 100 mg and mass measurement accuracy was 0.002 mg. The time to reach equilibrium for each point of the isotherm ranged between 20 to 24 h.

The structural characteristics of the cell wall, i.e. the specific surface area (**A**) accessible for water, water hydrophility ($\mathbf{a_m}$) (BET-method) and surface concentration of hydrophilic centres (α) were determined according to the procedure described by Chirkova et al. (2009). The value **A** was determined by the comparative method using the isotherm of water vapour sorption of cellulose as standard.

The total pore volume of wood cell wall swollen in water vapour ($\mathbf{W_s}$) at relative pressure $P/P_0 \approx 0.95$ corresponds to the FSP (**Paper II**).

2.3.3 Colour evaluation

A Konica Minolta CM-2500d surface reflectance spectrophotometer was used to determine the colour change at the surface of the specimens of ncurri and ntholo. Three-dimensional, *L**, *a** and *b** colour space by the Commission International de l'Eclairage (CIE) was used for colour evaluation. *L** specifies the lightness in a range from black (0) to white (100), *a** is red-green share and *b** is blue-yellow share. Both *a** and *b** are positive/negative co-ordinates defining the hue and intensity of the colour. Colour change (ΔE^*) was calculated according to equation 1.

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \qquad (1)$$

Where ΔL^*, Δa^* and Δb^* represent the changes of lightness (L_i^*) and chromatic parameters (a_i^* and b_i^*) between different parts of the boles. The colour evaluation procedures are detailed in **Paper II**.

2.4 Mechanical properties

Tests for determining the mechanical properties were carried out for metil (**Paper III**) and ntholo (**Paper IV**). The tests were performed on specimens at 12% MC by a using universal testing machine (Shimadzu AG-X 50 KN). The measurement accuracy was ±0.01 mm for position, ±0.1% for speed and ±0.5% for loading. Ntholo and metil heart- and sapwood specimens were randomly taken from five trees irrespective of their position in the logs. Thereafter the specimens were prepared according to methods and general requirements for mechanical tests as recommended by ISO 3129 (1975). The properties measured were:

- Modulus of elasticity according to ISO 3349 (1975);
- Modulus of rupture according to ISO 3133 (1975);
- Static hardness perpendicular and parallel to grain according to ISO 3350 (1975);
- Compression stress parallel to grain according to ISO 3787 (1976);

- Compression stress perpendicular to grain according to ISO 3132 (1975);
- Tensile strength according to ISO 3345 (1975); and
- Impact bending strength according to ISO 3348 (1975).

2.5 Relationship between wood anatomical characteristics, density and mechanical properties of ntholo

Clear samples (20×20×400 mm) representing sapwood and heartwood were prepared. The samples were taken from five ntholo trees regardless of their location within the logs. The tested physical-mechanical properties were density at 12% MC, Brinell static hardness, compression strength (parallel and perpendicular to grain), static bending strength (modulus of elasticity-MOE and modulus of rupture-MOR), tensile strength and impact bending strength. In parallel, being lesser used timber, the tested properties of ntholo were compared to the well known timbers to enable end use assessment.

2.5.1 Microscopy and anatomical descriptions

From all the tested specimens in static bending, small block were taken close to the failure points. They were then treated to obtain anatomical slides as described by Uetimane et al. (2009). The wood was softened before sectioning by autoclaving them repeatedly. Anatomical characteristics as described in **Paper IV**, i.e. fibre dimensions/morphology (length, wall thickness and diameter), vessel characteristics (diameter and number of vessels/mm^2) and average grand tissue composition (% fibres, % parenchyma including rays and % vessels) were determined.

For the natural durability study (**Paper V**), small wood pieces taken from the buried part of the specimens used in the soft rot test were cut, autoclaved in 10% glycerine and cut to 20-40 μm thick sections using a Leitz microtome sledge. The sections were stained with 1% safranin or lactophenol blue and observed with a Leica DMB light microscope. Images of fungal attack in the wood structure were recorded using a CCD camera.

2.5.2 Statistical analysis and modelling

Apart from tensile and impact bending, all tested mechanical properties along with density were interrelated to corresponding anatomical features in all specimens. The study explored relationships through a combined approach of correlation analysis, simple and multiple linear regressions. The correlation analysis was aimed to understand the association between pairs of all involved variables.

The anatomical features were assumed as independent variables while the density and the mentioned mechanical properties were regarded as dependent variables. Due to multicollinearity between some anatomical features, the study employed partial least square (PLS) and simple linear regressions using Minitab 15 software. The use of PLS allowed to identify key anatomical features exerting large influence on a given property through its coefficient. The models were represented according to equation 2.

$$Y = X1 + X2 + X3 + X4 + X5 + X6 + X7 + X8 \quad (2)$$

Where: *Y* is dependent variable (density at 12% MC, MOE, MOR, hardness or compression strength) and *X* is independent variable (*X1*=% Fibres; *X2*=% vessels; *X3*=% parenchyma tissues including rays; *X4*=number of vessels/mm^2; *X5*=vessel diameter; *X6*=Fibre length; *X7*=Fibre diameter; and *X8*=Fibre wall thickness).

The predictive capabilities of the generated models were assessed using the leave-one out cross validation method. Simple linear regression was used for practical reasons by taking density as independent variable to predict the studied mechanical properties (**Paper IV**).

2.6 Natural durability

The assessment of natural durability was performed according to European standards EN 350-1 (1994) through laboratory and field testing methods. The methods for assessing the natural durability considered in this study are detailed in **Paper V**. These were specifically:

- Soft rot test;
- Test with basidiomycetes;
- Termite standard and choice tests;
- In- and above ground field tests and weathering.

2.6.1 Soft rot test

The soft rot test was performed according to European standard prENV 807 (1993). Scots pine (*Pinus sylvestris* L.) sapwood and beech (*Fagus sylvatica* L.) were used as references. The soil for tests was obtained from Ultuna, Uppsala, where the prevailing decay organisms are soft rot fungi and bacteria (Edlund and Nilsson 1998). Bending tests aiming to assess the decrease of

MOE were carried out before exposure and after 8, 16, 24 and 32 weeks of exposure.

2.6.2 Test with basidiomycetes

The durability test against brown- and white rot fungi was carried out according to EN 113 (1996). Blocks 15×25×50 mm along the grain were used. The brown rot fungi used were *Coniophora puteana* BAM Ebw. 15, *Gloeophyllum trabeum* BAM Ebw. 109 and *Postia placenta* FPRL 280 and the white rot fungus was *Trametes versicolor* CTB 863A.

2.6.3 Termite standard and choice tests

Durability against termite attack through standard test was performed according to EN 118 (2005). Meanwhile, the termite choice test aiming to determine the termite feeding choice was also carried out according to EN 117 (2005). The termite species used for the first test was *Reticulitermes grassea*, while for the second test *Mastotermes darwiniensis* was chosen. Scots pine and black locust (*Robinia pseudoacacia* L.) samples were used as references. For the termite choice test the vessels were filled with a complete set of specimens. The specimens of various wood species were arranged in two rows as shown in Figure 1.

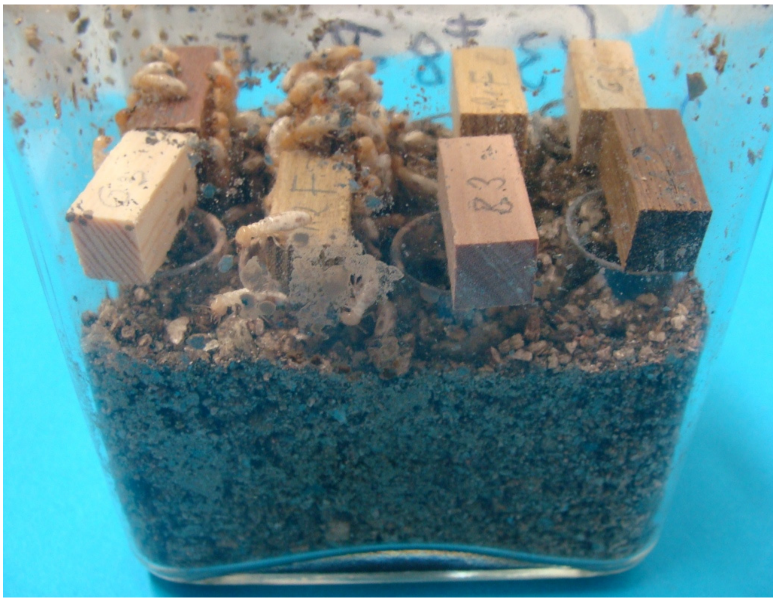

Figure 1 – Arrangement of wood specimens in a test vessel

2.6.4 Field tests

Wood durability tests in ground contact according to EN 252 (1989) and above ground according to ENV 12037 (1996) were initiated. The tests are ongoing in two fields, namely Marracuene (Mozambique) and Ultuna near Uppsala, Sweden. Heart- and sapwood specimens of muanga, metil, namuno, ncurri and ntholo were exposed in ground contact and examined annually. Only lap-joints of ncurri sapwood and heart- and sapwood of ntholo were exposed in an above ground test in Ultuna. The weight of the lap-joints exposed in Ultuna was evaluated before exposure and bimonthly over one year. The colour change of the lap-joints was monitored twice, after six and eighteen months of exposure. Collected data were used to determine the water uptake of wood and its colour change. Three-dimensional L^*, a^* and b^* colour space by CIE was used to quantify colour change (ΔE^*).

3 Results and discussion

3.1 Situation of timber sector in Mozambique

This part of study outlines the situation of timber sector in Mozambique (**Paper I**). The study considered the current situation of the most sought-after and commercialised timber species in the country. It also discussed the prospects and highlighted the contribution of the timber sector to the country's economy. The results proved that the intensive selective logging system employed in the country may turn problematic in the near future. The after effect of the current logging regime is the abandoning of vast forest concessions after short periods of exploitation because the major species were nearly exhausted. From this, it might be deducted that untapped forests from which commercial-sized well known timber species can be cut are becoming rarer in Mozambique. This fact is likely to contribute to the rapid depreciation of the forests leading to loss of the capability of the timber sector to remain economically viable in the country.

A major market constraint specific to lesser used timber species is the lack of technical data for development of processing capabilities (Easton and Wright 1998; Barany et al. 2003). Undoubtedly, information regarding wood properties is required for best timber utilization (Josue 2004; Chowdhury et al. 2007). Therefore, **Paper I** stressed the urgent need to acquire more information on wood properties of abundant but lesser known/used timber species in Mozambique. This is likely to reduce pressure on the better known wood species and increase the volume of wood extracted per unity area, enabling the harvesting to be more economically viable. A comparison of some wood physical and mechanical properties between two lesser known/used species and well-known species has shown encouraging findings (**Paper I**). Table 2 compares the density at 12% MC and some mechanical properties of two lesser used species to those of two well known species.

Table 2 – Comparison of density and some mechanical properties of muanga, metonha, chanfuta and umbila

Property	Lesser used species		Well known species	
	Muanga	Metonha	Chanfuta	Umbila
Density [kg/gm^3]	865	780	670	590
Janka hardness [N]	6939	1340	8229	6583
Impact bending [KJ/mm^2]	75.6	-	79.2	57.1

As shown in Table 2, muanga has higher density, hardness and impact pending strength than umbila. It is also superior in density, somewhat equal in impact bending, but inferior in hardness when compared to chanfuta. Metonha is superior in density although inferior in hardness. Generally, density is related to wood mechanical properties. Both muanga and metonha have higher density than chanfuta and umbila which indicates that the former two species can be used in the same applications as the latter two, if strength is a key factor. However, this cannot be taken for granted. Therefore, research on wood properties and natural durability of abundant but overlooked wood species is needed in Mozambique. This will enable the diversification of species in the country's timber market and reduction of pressure on well known species.

3.2 Physical properties

This part presents and discusses in brief the results obtained from the studies on some wood physical properties of ncurri and ntholo (**Paper II**) and metil (**Paper III**).

3.2.1 Density, moisture content, shrinkage and swelling

Table 3 shows the average and coefficient of variation values of density at 12% MC, green MC, shrinkage and swelling of ncuri, ntholo and metil. There were noticeable differences in densities among the three species. Metil had the lowest value of density while ntholo had the highest. For example, the density at 12% MC of metil on average was 550.6 kg/m^3 and ranged between 465.1 and 647.5 kg/m^3. For ntholo heartwood this value was 1023.4 kg/m^3 and ranged between 882.9 and 1136.2 kg/m^3, while ncurri averaged 907.1 kg/m^3 and was ranged between 834.2 and 973.2 kg/m^3. The values of density (green, at 12% MC, oven-dry and basic) of heart- and sapwoods of ncurri and ntholo (**Paper II**) showed lower coefficients of variation than those of metil (**Paper III**).

Ntholo coefficients of variation are generally lower in heartwood than in sapwood. For example, the coefficient of variation of basic density is 5.0% for the heartwood and 6.7% for the sapwood. The difference is even larger at 12% MC where the coefficient of variation is 5.1% for heartwood and 8.3% for sapwood (**Paper II**). It can be assumed that ntholo sapwood has higher variability in density than the heartwood. The same situation also occurs in ncurri where the heartwood had coefficients of variation of 3.5% for density at 12% MC and 3.6% for basic density. For sapwood these values were 4.1% for density at 12% MC and 4.6% for basic density (**Paper II**).

Table 3 – Fundamental physical properties of ncurri, ntholo and metil

Physical properties		Timber species					
		Ncurri		Ntholo		Metil	
		Mean	CV (%)	Mean	CV (%)	Mean	CV (%)
Density at 12% MC [kg/m^3]		907.1	3.5	1023.4	5.1	550.6	7.2
Green MC [%]		29.5	12.2	39.2	10.7	53.2	4.1
Shrinkage from green to oven-dry	Radial [%]	5.7	22.8	5.8	20.7	3.8	28.0
	Tangential [%]	7.0	17.1	7.4	14.9	6.6	26.0
	Longitudinal [%]	0.2	150.0	0.3	66.7	0.2	1.5
	Volumetric [%]	12.4	12.9	13.0	9.2	10.3	21.0
	C. of anisotropy	1.3	30.8	1.4	35.7	1.8	28.0
Maximum swelling	Radial [%]	6.4	25.0	5.8	20.9	3.7	32.0
	Tangential [%]	8.7	14.9	7.5	13.9	6.5	23.0
	Longitudinal [%]	0.2	100.0	0.1	40.0	0.1	10.0
	Volumetric [%]	16.0	12.5	12.9	9.2	10.0	21.0

CV – coefficient of variation

The variation of density along radial direction is shown in Figure 2 by means of 95% confidence interval (CI) plots for the average values of density at 12% MC at breast height for ncurri, ntholo and metil. Figure 2 indicates that the density does not vary noticeably from pith towards the cambium in metil and ncurri. Similar patterns were reported for some hardwood species such as *Populus euramericana* Guinier (Kord et al. 2010), *Eucalyptus citriodora* Hook (Shashikala and Rao 2009) and *Alstonia boonei* De Wild (Zziwa et al. 2006). In ntholo the density reduced gradually in the heartwood but decreased abruptly in the sapwood towards cambium. One explanation of the noticeable radial change of density in ntholo is likely not only to be associated with the presence of greater amount of extractives in the heartwood than in the sapwood, but also the living part that is probably not lignified.

The variation of density along the bole height decreased insignificantly from bottom to top along the tree height in ncurri, ntholo and metal (Table 4). The average density at 12% MC of metil decreased with only a few kilograms, the density of ntholo at 12% MC was 1048.6 kg/m^3, 1006.8 kg/m^3 and 1005.7 kg/m^3 for bottom, middle and top part respectively. The trend was observed also in ncurri where the density at 12% MC was 929.2 kg/m^3 (bottom) and 885.0 kg/m^3 (middle). Similar pattern of variation was reported for *Casuarina equisetifolia* (Chowdhury et al., 2007). This is a general trend since wood density is usually higher at bottom due to the higher compaction of the stump tissues exerted by overlapping cells along the bole and tree crown.

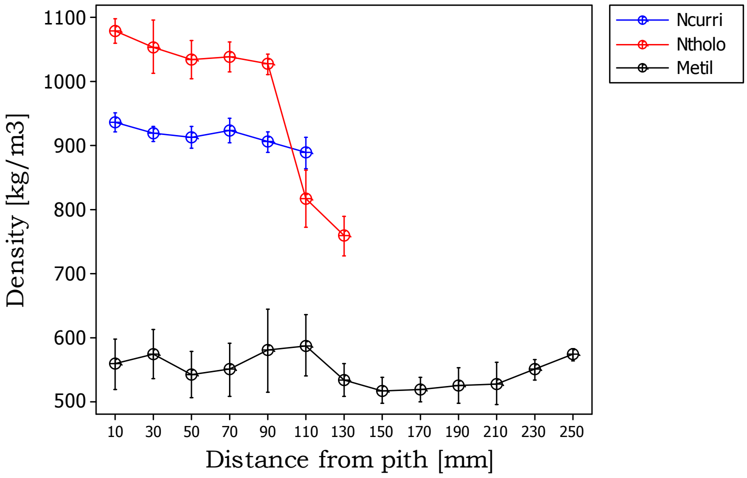

Figure 2 – Variation of density at 12% MC along radial direction at breast height of bole

Regarding green MC, the average values for heartwood were 29.5 for ncurri, 39.2 for ntholo and 53.2 for metil. These values indicate low amount of free water in the wood structure of the three species. This may be an important factor for kiln drying operations to prevent development of internal stresses that may require mild initial drying stage (**Paper II**).

Figure 3 represents the variation of MC along the radial direction by plotting the 95% CI of the means for ncurri ntholo and metil at breast height. It can be observed that the variation of green MC is nearly constant from pith towards the cambium in metil and ncurri. It gives the impression that both the heart- and sapwood of these species have the same value. The variation of green MC in ntholo is nearly constant in heartwood, but rises considerably in sapwood. Indeed, the analysis of variance (ANOVA) at 95% level of confidence showed that there is no significant difference in green

MC between heartwood and sapwood in metil and ncurri. The difference in heart- and sapwood green MC of ntholo was significant. No significant variations of the green moisture content were observed along the tree height in the studied species (Table 4).

Paper II gives the average shrinkage values of ncurri heartwood from green to oven-dry as 5.7% for radial, 7.0% for tangential and 12.4% for volumetric. These values were larger than those of sapwood being 4.2% radial, 6.7% tangential and 10.8% volumetric. A similar situation was also observed in ntholo where the shrinkage values from green to oven-dry for heartwood were 5.8% for radial, 7.4% for tangential and 13.0 for volumetric, while for sapwood the values were 4.0, 6.5 and 10.4% respectively for radial, tangential and volumetric (**Paper II**). This may be explained by differences in density between the heart- and sapwoods, because a larger shrinkage is associated with higher density of wood (Bowyer et al. 2003).

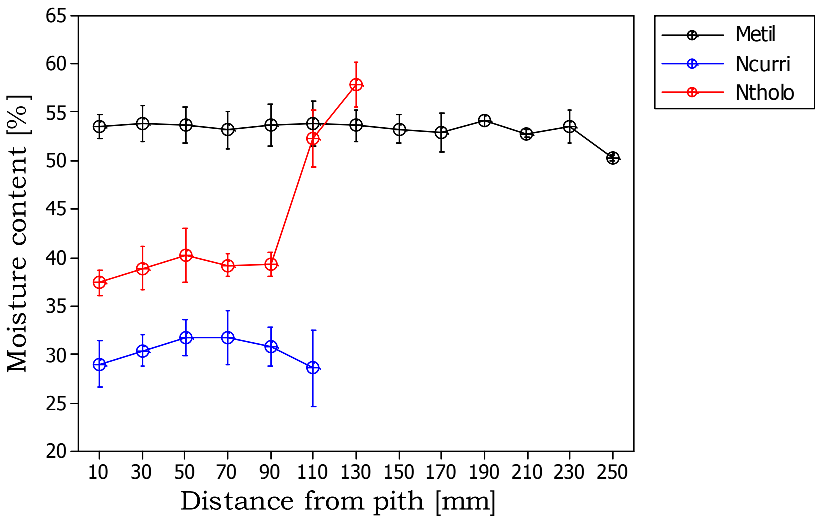

Figure 3 – Variation of green MC along the radial direction at breast height of a bole

The coefficients of anisotropy of heartwood of ntholo were 1.4 for green to oven-dried shrinkage and 1.5 for green to 12% MC shrinkage. These coefficients were 1.6 and 1.9 for the sapwood. These observed values are low which indicates that the species is highly homogeneous and dimensionally stable. Thus, ntholo can be used where small dimensional changes are required. For example, it can be used for building joinery (doors and windows frames or flooring) tool handles and furniture.

Table 4 shows shrinkage anisotropy variation of metil, ncurri and ntholo. The anisotropy in axial direction does not vary significantly in ntholo and ncurri, while in metil the shrinkage anisotropy variation is higher. The relative within-tree stability and homogeneity of ntholo regarding shrinkage is favourable, because the wood might be less prone to significant deformations during drying (Pliura et al. 2005). After laboratory batch kiln drying of 1.0 m long boards, Uetimane et al. (2010) reported low deformation values in ntholo. These were on average 1.0 mm for bow, 1.1 mm for crook, 3.4 mm for twist and 0.6 mm for cup. From these values ntholo is classified as a standard quality wood species according to indicators recommended for assessment by the European drying standards (Uetimane 2010).

Table 4 – Variation of metil, ntholo and ncurri density, green moisture content and shrinkage anisotropy along axial direction

Property	Wood species	Section of bole		
		Bottom	Middle	Top
Density at 12% MC [kg/m^3]	Metil	553.6 (37.6)*	553.4 (37.7)	530.9 (47.4)
	Ntholo	1048.6 (54.0)	1007.6 (52.8)	1005.7 (28.9)
	Ncurri	929.2 (25.2)	885.0 (20.2)	–
Green MC [%]	Metil	53.4 (2.2)	53.5 (2.3)	52.8 (2.0)
	Ntholo	39.0 (3.6)	39.1 (5.6)	39.7 (2.7)
	Ncurri	29.9 (3.4)	29.1 (3.7)	–
Coefficient of anisotropy	Metil	2.0 (0.6)	1.7 (0.4)	1.6 (0.3)
	Ntholo	1.3 (0.2)	1.3 (0.3)	1.4 (0.6)
	Ncurri	1.4 (0.4)	1.2 (0.3)	–

* Average value and standard deviation in parentheses

The variation of shrinkage along radial direction was investigated for ncurri and ntholo (**Paper II**) and also metil (**Paper III**). This is presented by mean of 95% CI plots for the average shrinkage (radial, tangential and volumetric) from green to oven-dry at breast height for the three timber species. At breast height the shrinkage was somewhat higher near the pith. In ntholo and metil the radial and tangential shrinkages were nearly constant from the pith outwards and then decreased near the bark. In ncurri it was almost constant along the radius, although with general tendency to decrease. The radial variation of volumetric shrinkage of ncurri, ntholo and metil followed the pattern of tangential shrinkage, because the latter contributed the most to the total volumetric shrinkage (Pliura et al. 2005). The variation of shrinkage with tree height was also studied and was found to decrease from bottom to top in heartwoods of both ncurri and ntholo (**Paper II**). A similar pattern of variation of shrinkage from bottom to top was observed in the sapwoods. In metil the shrinkage also decreased from bottom to top (**Paper III**).

The average values of maximum swelling of heartwood of ncurri were 6.4% for radial, 8.7% for tangential and 16.0% for volumetric (**Paper II**). These values are slightly greater than those of sapwood (i.e. 5.0% radial, 8.3% tangential and 13.9% volumetric). The difference in maximum swelling between heartwood and sapwood in ntholo was noticeable, being greater in heartwood (5.8% for radial, 7.5% for tangential and 12.9% for volumetric) than in sapwood (4.1% radial, 6.6% tangential and 10.6% volumetric) (**Paper II**). The larger difference in swelling between the heartwood and sapwood observed in ntholo can be associated with the greater difference in wood density between these parts of wood, as density is an important factor that significantly influences swelling (Mantanis et al. 1994). Therefore, in ncurri, where the difference of density between heart- and sapwood is smaller, the difference of swelling between these parts of wood is also smaller. Furthermore, the average values of maximum swelling of metil were 3.7% for radial, 6.5% for tangential and 10.0% for volumetric (**Paper III**). These values are generally lower than those observed in ncurri and ntholo. This can be explained by a lower density of metil than those of ncurri and ntholo.

3.2.2 Water vapour sorption and desorption

The sorption-desorption isotherms of water vapour were studied for ncurri and ntholo and shown in Figure 4 together with the isotherm of Scots pine for comparison purpose.

Figure 4a shows that when the relative pressure of saturated vapour is equal to 0.95, the sorption isotherms reach values of 28% MC for ncurri and 25% MC for ntholo. These values could be accepted as FSP. The higher value of FSP of ncurri is explained by its lower density and higher swelling.

Wieringa (1999) reported the presence of rare prismatic crystals in chambered axial parenchyma cells of ncurri. Uetimane et al. (2009) also reported the presence of mineral crystals stored in the vessel and parenchyma cells of ntholo. Cuvilas (2009) reported that the amount of extractives in the heartwood of ntholo was twice that of ncurri. Thus, the lower FSP of ntholo wood might be explained by its higher extractive content. This is in line with the findings of Choong and Achmadi (1991) who stated that FSP may be lower in wood with high extractive contents, such as in many tropical species. Nevertheless, ntholo is closer to Scots pine wood in terms of hydrophilic properties.

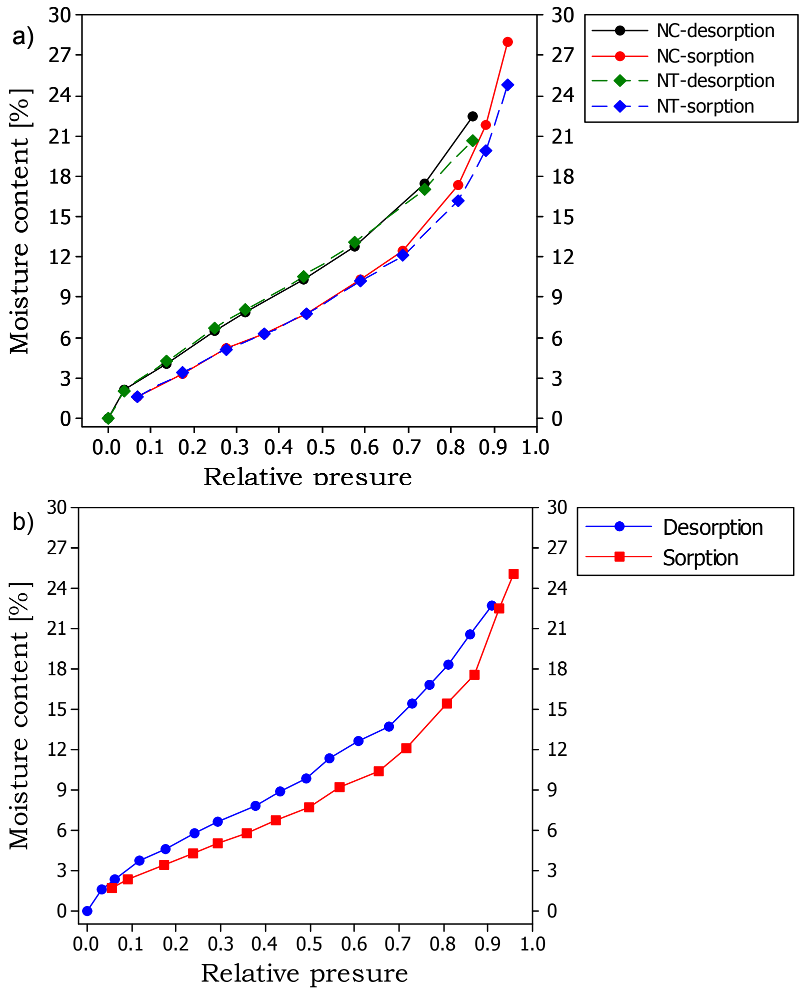

Figure 4 – Moisture sorption-desorption isotherms: a) ncurri and ntholo; b) Scots pine (NC – ncurri; NT – ntholo)

The cell wall of ncurri is more hydrophilic than that of ntholo (**Paper II**). Figure 5 shows the structural curves for the distribution of pore volume in pore sizes for ncurri and ntholo. The distinction in the porous structure of ntholo and ncurri cell wall swollen in water vapour fall in the region of the pore width 2-7 nm, where the ncurri pore volume is somewhat higher than that of ntholo.

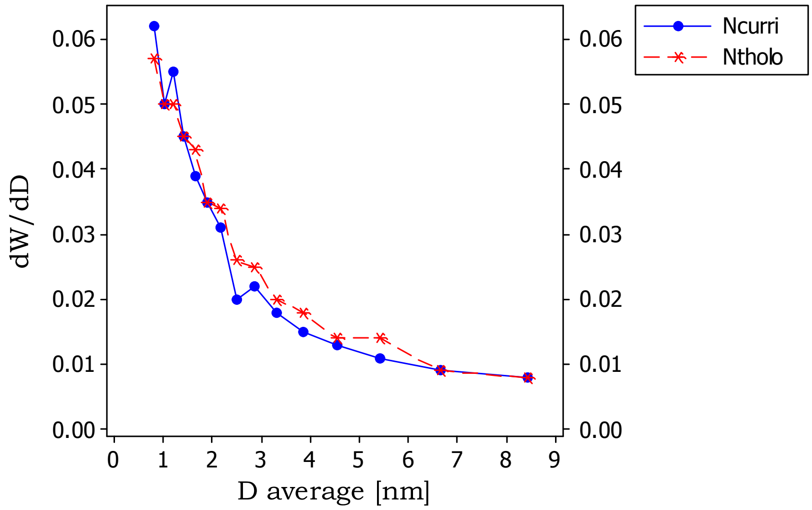

Figure 5 – Distribution of pore volume in pore sizes for ncurri and ntholo

3.2.3 Colour evaluation

Wood colour is a determining wood property for marketing and for manufacturing of various products as furniture or wooden ornaments such as floorings, claddings, decorative veneers and others (Aguilar-Tovar et al. 2009). Therefore, the study of timber colour variation is important.

The colour parameter lightness (*L**), redness share (*a**) and yellowness share (*b**) were measured in ncurri and ntholo and presented as average values and standard deviations. These were 62.0 ± 8.9 for *L**, 11.4 ± 2.2 for *a** and 23.4 ± 2.7 for *b** in ncurri heartwood. The corresponding values in ntholo heartwood were 45.3±4.1, 11.5±1.5 and 15.1±2.6 for *L**, *a** and *b** respectively (**Paper II**).

A comparison of the chromatic parameters shows that on average the redness (*a**) was lower than the yellowness (*b**), in both species. In addition, the lightness (*L**) was on average higher in sapwood (76.38) than in heartwood (62.01) in ncurri. The colour characterisation of ncurri might be described as light yellowish-brownish heartwood and very light yellowish sapwood. In ntholo the *L** values were on average 45.32 for heartwood and 59.16 for sapwood (**Paper II**). The sapwood of ntholo was observed to be yellowish in colour, while the heartwood was dark brown. Ntholo heartwood is comparable to jambire in colour and can be used for decorative purposes because of its beauty.

The variation of colour along the radial direction was considered for ncurri and ntholo. This is shown through the 95% CI plots for the mean values of lightness (*L**), redness share (*a**) and yellowness share (*b**) at breast height for both speciesin **Paper II**. This indicated a general trend of increased lightness and yellowness from the pith outwards in both species, while the redness increased in ntholo and decreased in ncurri (**Paper II**). This indicates that the species are darker in the inner and lighter in the outer parts of the stem.

3.3 Mechanical properties

This part is aimed to outline and discuss the measured mechanical properties of metil (**Paper III**) and ntholo (**Paper IV**). Experimental results for MOE, MOR, compressive strength parallel and perpendicular to grain, tensile strength, hardness parallel and perpendicular to grain and impact bending at 12% MC of ntholo and metil are presented in Table 5. Ntholo showed higher strength values than metil. For example, the average values of MOE of ntholo, were 17263.0 N/mm^2 for heartwood and 10326.7 N/mm^2 for sapwood. The MOE of metil was considerably lower being on average 5800.0 N/mm^2. The average values of MOR for ntholo were 119.2 N/mm^2 for heartwood and 100.9 N/mm^2 for sapwood. This value was on average 54.0 N/mm^2 for metil. The average values of compression, tensile and impact bending strength were also considerably higher in ntholo than in metil (Table 5). This can be associated with a considerable difference in density between the two species.

Table 5 – Principal mechanical properties of ntholo and metil

Mechanical properties	Ntholo		Metil	
	Average	CV (%)	Average	CV (%)
MOE [N/mm^2]	17263.0	20.6	5800.0	9.6
MOR [N/mm^2]	119.2	13.0	54.0	9.0
Compression // to grain [N/mm^2]	55.7	14.7	26.0	12.8
Compression ⊥ to grain [N/mm^2]	27.5	15.6	7.4	19.1
Tensile strength [N/mm^2]	78.6	24.0	42.9	40.1
Hardness // to grain [HB]	7.2	14.8	4.5	11.3
Hardness ⊥ to grain [HB]	4.3	11.7	1.7	7.7
Impact bending [kJ/mm^2]	81.5	43.2	43.1	15.9

CV – coefficient of variation; HB – Brinell hardness.

Regarding wood mechanical properties, the arrangement and proportions of ground tissues (axial and ray parenchyma, fibres and vessels) in hardwood species are considered to play a key role (Barnett and Jeronimidis 2003; Bowyer et al. 2003). Uetimane et al. (2009) reported some large differences in ground tissue proportions between wood structures of ntholo and metil. On average, the ray parenchyma was 22% in ntholo and 19% in metil; the axial parenchyma was 8% in ntholo and 53% in metil; the vessels represented 14% in ntholo and 6% in metil and the fibres were amounted to 57% in ntholo and 22% in metil (Uetimane et al. 2009). Thus, the difference in strength parameters between ntholo and metil timbers may also be accounted by their differences in anatomical structures.

3.4 Relationship between wood anatomical characteristics, density and mechanical properties of ntholo

This study examined the relationship between wood anatomical characteristics and physical-mechanical properties. For this, density and some mechanical properties of ntholo were interrelated with selected wood anatomical features, namely the ground tissue proportions (average composition in percentage), fibre dimensions (diameter, length and cell wall thickness) and also vessels (vessel diameter and number of vessel per mm^2). Furthermore, density was also related to the tested mechanical properties due to its practical importance in predicting the wood strength.

3.4.1 Correlations between wood anatomical characteristics, density and mechanical properties

A correlation analysis to reveal and discuss the observed associations between sub-sets or pairs of variables (anatomical features and measured properties) from the same specimen was carried out and the results are presented in a full correlation matrix table in the **Paper IV**. A complete matrix presenting the correlation coefficients observed for ntholo heart- and sapwood samples is given in Table 6.

The correlation between wood density and measured mechanical properties is similar to that found by Armstrong et al. (1984) for other hardwood species. Ntholo density was significantly correlated to some of the tested mechanical properties. For example, ntholo heartwood showed a positive and significant correlation between density and MOR (in static bending) and also hardness perpendicular to grain. Density produced positive and non-significant correlation to the MOE, compression strength (parallel and perpendicular to grain) and hardness parallel to grain. In contrast to the heartwood, the sapwood showed significant positive correlation of both MOE and MOR with density (**Paper IV**). Meanwhile, the hardness perpendicular to grain of heartwood was significantly and positively correlated to density.

Table 6 – Correlation coefficients between density, anatomical characteristics and mechanical properties of ntholo

Anatomical features and density	Mechanical properties					
	Static bending		Compression strength		Brinell hardness	
	MOE	MOR	// to grain	⊥ to grain	// to grain	⊥ to grain
Heartwood						
% Fibres	0.214	0.063	-0.029	0.166	0.150	-0.198
% Vessels	0.187	0.277	-0.046	-0.382	0.076	-0.257
% Parenchyma tissues	0.264	0.154	0.043	-0.023	-0.167	0.273
Nr. of vessels/mm^2	0.293	0.025	0.029	-0.068	0.024	-0.104
Vessel diameter	0.208	0.363	-0.062	0.066	0.295	-0.215
Fibre length	0.268	0.259	-0.610*	-0.425	0.013	-0.449*
Fibre diameter	0.530*	0.374	-0.347	-0.50*	-0.230	-0.317
Fibre wall thickness	0.021	0.098	-0.447*	-0.307	0.098	-0.103
Density at 12% MC	0.256	0.520*	0.201	0.298	0.307	0.561*
Sapwood						
% Fibres	0.338	0.527*	-0.228	-0.372	0.282	-0.355
% Vessels	-0.072	-0.014	0.037	0.342	-0.021	0.002
% Parenchyma tissues	-0.288	-0.55*	0.219	0.182	-0.285	0.375
Nr. of vessels/mm^2	-0.390	-0.200	0.083	0.409	-0.034	-0.037
Vessel diameter	-0.187	0.041	-0.074	-0.073	-0.56*	-0.428
Fibre length	0.697*	0.471*	-0.127	-0.52*	0.243	0.015
Fibre diameter	0.117	0.159	0.295	0.164	0.090	0.087
Fibre wall thickness	-0.49*	-0.284	0.232	0.155	-0.192	0.142
Density at 12% MC	0.486*	0.463*	-0.119	-0.70*	0.226	-0.102

* Significant correlation coefficients at p=0.05

The study found some significant correlations between anatomical features and density, although rather weak coefficients of determinations were observed. In fact, the heartwood density of ntholo was partially correlated to % parenchyma tissue including rays, while the density of sapwood was proportional to the fibres length (**Paper IV**).

A significant association between some elasticity parameters and fibre dimensions were observed in ntholo heartwood sample. For example, high values of MOE were associated with large fibre diameters. Fibre dimensions were also negatively correlated to both parallel and perpendicular to grain compressive loadings. Specifically, fibre length and fibre wall thickness were significantly correlated to compression parallel to grain, while fibre diameter was correlated to compression perpendicular to grain. The fibre length was inversely correlated to hardness perpendicular to grain.

3.4.2 Prediction of density and mechanical properties from wood anatomical features

The prediction of ntholo density and mechanical properties was carried out through partial least squares (PLS) regression analysis. These were conducted to construct statistical models to identify important predictor variables (anatomical features) exerting large influence on measured properties. The final models obtained are given in the **Paper IV**. The MOE of sapwood produced the only significant regression equation, while for heartwood, non-significant regression equations were observed for all measured properties.

Nevertheless, the models suggest that the variation of the tested sapwood properties are controlled by tissue proportions and are negatively related to them, apart from hardness parallel to grain which is positively related. In relation to heartwood properties, the model suggests that density is negatively affected by vessel proportion and positively affected by fibre wall thickness. The models also suggest that there were no clear leading factors for MOR, despite the fibre diameter and the number of vessels/mm^2 having relatively larger coefficients. For MOE, fibre dimensions seem to be major predictors.

3.4.3 Prediction of wood mechanical properties from density

Wood density is acknowledged to affect mechanical properties (Barnett and Jeronimidis 2003; Bowyer et al. 2003). Earlier studies examined the predictability of some wood mechanical properties from density on various hardwood species such *Hevea brasiliensis* (Gnanaharan and Dhamodaran 1992), *Eucalyptus globulus*, *E. nitens* and *E. regnans* (Yang and Evans 2003), *Celtis mildbraedii* and *Maesopsis eminii* (Zziwa et al. 2006). These studies reported density as a good estimator of mechanical properties in some timber species. However, in other species density was a poor predictor. The capability of ntholo density as predictor of some mechanical properties through simple linear regression is given in Table 7 for heart- and sapwood samples.

As shown in Table 7, the density of ntholo is a poor estimator of measured mechanical properties. Hence, in the majority of cases the coefficient of determination (R^2) was less than 20 %. The highest value of R^2 was observed for compression perpendicular to grain in sapwood, where density alone accounted for approximately 46% of the variation of compressive strength (**Paper IV**). In the heartwood, the maximum value of R^2 was nearly 28%, indicating even poorer predictability of mechanical properties from density alone. Poor predictability of some mechanical properties from density alone was reported for cleavage strength, compression parallel to grain, MOE, MOR and work to maximum load for *H. brasiliensis*, *Celtis mildbraedii* and *Maesopsis eminii* (Gnanaharan and Dhamodaran 1992; Zziwa et al. 2006).

Table 7 – Prediction of mechanical properties from density through linear regressions

Wood part	Mechanical properties	Linear regression expressions	R^2_{adj} (%)	p value
Heartwood	MOE	$0.187\boldsymbol{d} - 72.2$	23.2	0.016
	MOR	$-21.1\boldsymbol{d} + 338880$	1.6	0.263
	Compression // to grain	$0.0646\boldsymbol{d} - 36.6$	0.0	0.382
	Compression ⊥ to grain	$0.0821\boldsymbol{d} - 70.9$	4.1	0.189
	Hardness // to grain	$0.00762\boldsymbol{d} - 0.59$	4.7	0.175
	Hardness ⊥ to grain	$0.0066\boldsymbol{d} - 2.44$	27.9	0.008
Sapwood	MOE	$17.1\boldsymbol{d} - 2679$	19.4	0.03
	MOR	$0.196\boldsymbol{d} - 47.7$	17.1	0.04
	Compression // to grain	$-0.04d + 57.8$	0.0	0.61
	Compression ⊥ to grain	$-0.142\boldsymbol{d} + 115$	45.8	0.001
	Hardness // to grain	$0.005\boldsymbol{d} + 1.57$	0.0	0.338
	Hardness ⊥ to grain	$-0.00063\boldsymbol{d} + 3.36$	0.0	0.67

d – Density at 12% MC; R^2_{adj} – adjusted coefficient of determination.

3.5 Natural durability

Knowledge about the natural durability of wood species can provide useful information on their possible end-uses as well as important predictions on product service life (Gambetta et al. 2004). This part presents and discusses results obtained from the study on natural durability of metil, muanga, namuno, ncurri and ntholo. Details of the durability studies are given in **Paper V**.

3.5.1 Soft rot test

The durability evaluation of the studied timber species against soft rot fungi is shown in Figure 6 through the 95% confidence intervals of mass loss (ML). Figure 6 compares the ML caused by soft rot fungi of heartwoods of metil, muanga, namuno, ncuri and ntholo with those of reference species (beech and pine sapwood).

Figure 6 show that metil was the least durable among the tested wood species. According to prENV 807, the ML of 48.6% after 32 weeks of exposure indicates that metil is non durable against soft rot like reference beech (with ML of 40.4%). The ML of heartwoods of muanga, namuno, ncurri and ntholo were 5.7%, 8.7%, 10.1% and 4.5%. These values are considerably lower than that of beech. This indicates that the four species are highly durable against sot rot fungi.

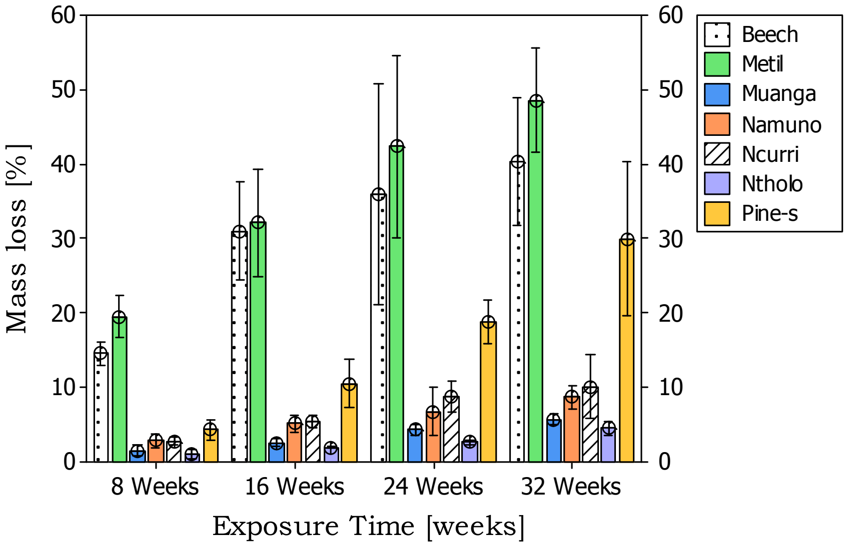

Figure 6 – Average and 95% confidence intervals of mass loss for the studied wood species after soft rot test according to ENV 807. Reference species: beech and pine sapwood

Cuvilas (2009) reported that the extractive content of the heartwood of muanga was five times higher than that of metil. Namuno and ntholo had respectively three times and twice ther amount of extractives than metil. In contrast ncurri had nearly the same amount of extractives as metil, although slightly higher. This suggests that the lower durability of metil is probably because of its lower extractive content. Extractive compounds in heartwood are recognized as the most important factor in determining the natural durability of wood (Bamber and Fukazawa 1985; Taylor et al. 2002).

Paper V outlines the gradual strength reduction caused by soft rot fungi assessed thorough the MOE decline over exposure time. Metil showed higher MOE loss among the studied species. This confirms that metil is the least durable, even when compared to beech and pine sapwood. This is emphasized by the fact that the MOE of metil and beech after 24 and 32 weeks of exposure was not assessed because the specimens were too rotten (**Paper V**). The same situation occurred for pine sapwood after 32 weeks exposure.

The observed action of soft rot measured by ML and MOE decline are illustrated by wall cavities and spores in ntholo sapwood (Figure 7). In Figure 7A cross section of fibres shows the presence of cell wall cavities. Figure 7B shows scattered spores from fungal replication, while Figure 7C shows the typical hexagonal cavities in the fibre cell walls.

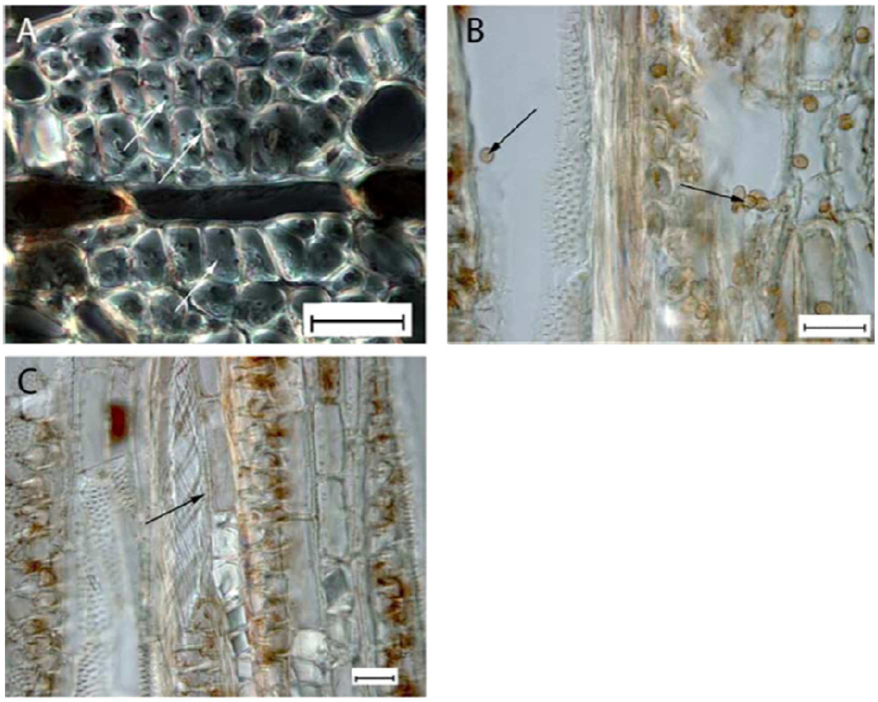

Figure 7 – Micrographs showing the decay features of ntholo sapwood after a soft rot test according to ENV 807. The arrows show typical cell wall cavities caused by soft rot (Fig. 7A), scattered spores that indicate fungal replication (Fig. 7B) and spirally oriented hexagonal cavities produced inside the cell wall (Fig. 7C). The bars correspond to 10 µm

3.5.2 Test with basidiomycetes

The mean (95% confidence intervals) ML after exposure to basidiomycete fungi for heartwoods of metil, muanga, namuno, ncurri and ntholo are shown in Figure 8 by comparing decay resistance of studied timber species against three brown rot (*C. puteana, G. trabeum* and *P. placenta*) and one white rot (*T. versicolor*) fungi.

Figure 8 gives some negative values of average ML caused by the three brown rot fungi for muanga, namuno and ntholo. The appearance of these values is explained by increase in MC caused by fungal respiration, i.e., oxidative degradation of carbohydrates with the consequent release of water molecules (Borrega et al. 2009). Thus, they indicate that there was no physical ML among these species.

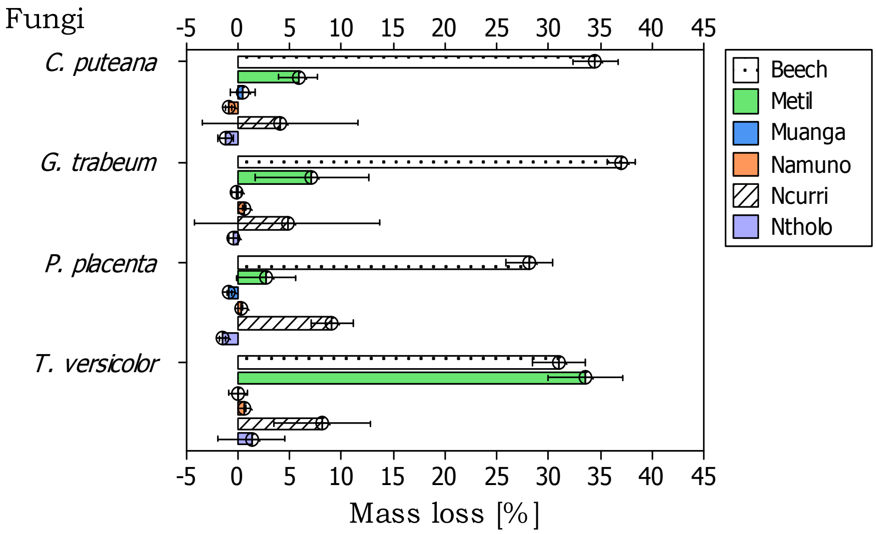

Figure 8 – Average and 95% confidence intervals of mass loss for the studied wood species after basidiomycete fungi test according to EN 113. Reference species: beech

As shown in Figure 8, metil showed the highest ML compared to the other wood species. There were almost no ML among the heartwoods of muanga, namuno and ntholo caused by the three brown rot fungi. Only the white rot fungus *T. versicolor* caused on average low ML on the last three timbers. Even so, these wood species are highly resistant against *T. versicolor*.

3.5.3 Comparison between durability tests

Large differences between the percentage ML caused by soft rot fungi (Figure 6) and basidiomycete fungi (Figure 8) were observed. While the soft rot fungi caused severe ML in the studied wood species, the ML caused by basidiomycete fungi was generally lower (**Paper V**). For example, the basidiomycete fungi caused on average a ML below 2% on the most durable timber species such as muanga, namuno and ntholo, while the soft rot fungi caused a ML above 4% on the same species. This is consistent with Van Acker et al. (1999) who found the durability classification derived from basidiomycete testing is not always relevant when considering soft rot fungi.

A comparison between the severity of fungal action of soft rot and basidiomycete fungi was carried out using the classification in durability classes of the studied timbers according to EN 350-1 (Table 8).

Table 8 – Classification of durability according to EN 350-1 based on results from the test methods ENV 807 and EN 113

Wood species	Basidiomycete fungi								Soft rot fungi	
	Coniophora puteana		*Gloeophyllum trabeum*		*Postia placenta*		*Trametes versicolor*			
	x* value	DC	x* value	DC	x* value	DC	x* value	DC	x* value	DC
Metil	0.17	2	0.19	2	0.10	1	1.08	5	1.21	5
Muanga	0.01	1	-0.01	1	-0.03	1	0.00	1	0.14	1
Namuno	-0.03	1	0.02	1	0.01	1	0.02	1	0.22	2
Ncurri	0.12	1	0.13	1	0.32	2	0.26	2	0.25	2
Ntholo	-0.03	1	-0.01	1	-0.06	1	0.04	1	0.11	1

1 - very durable; 2 - durable; 3 - moderately durable; 4 - slightly durable; 5 - not durable; DC – durability class; x* value is equal to average corrected mass loss of test specimens divided by the average mass loss of reference specimens.

It can clearly be observed that the action of soft rot was more severe than that of basidiomycete fungi. Hence, among the four basidiomycete fungi used, only the white rot *T. versicolor* caused some decay of the studied timbers. It was, nevertheless, less severe than that caused by soft rot fungi. The classification of metil in durability against the brown rots (*C. puteana*, *G. trabeum* and *P. placenta*) fluctuated between 1 (very durable) and 2 (durable). However, it was 5, i.e. not durable against the white rot fungus *T. versicolor* and also for soft rot fungi. This indicates that metil is perishable if exposed to either soft rot or white rot fungi. The durability rating of ncurri heartwood was 1 (very durable) against *C. puteana* and *G. trabeum*, but it was shifted to 2 (durable) against *P. placenta* and *T. versicolor*. The durability class of heartwoods of munga, namuno and ntholo was 1 and remained unchanged against the four basidiomycete fungi and also soft rot. This indicates that the last three timbers are highly durable against fungi.

3.5.4 Termite tests

Paper V presents and discusses in detail the results of visual rating of termite standard and choice tests and classified the studied timbers in terms of durability according to EN 350-1. The results showed that metil is susceptible and ncurri is moderately durable to termite attack. Muanga, namuno, and ntholo are highly durable. Figure 9 gives the general appearances of some of specimens after the termite standard test where it is apparent that metil was the only species intensely attacked. Ncurri was slightly attacked, while muanga, namuno and ntholo were almost untouched.

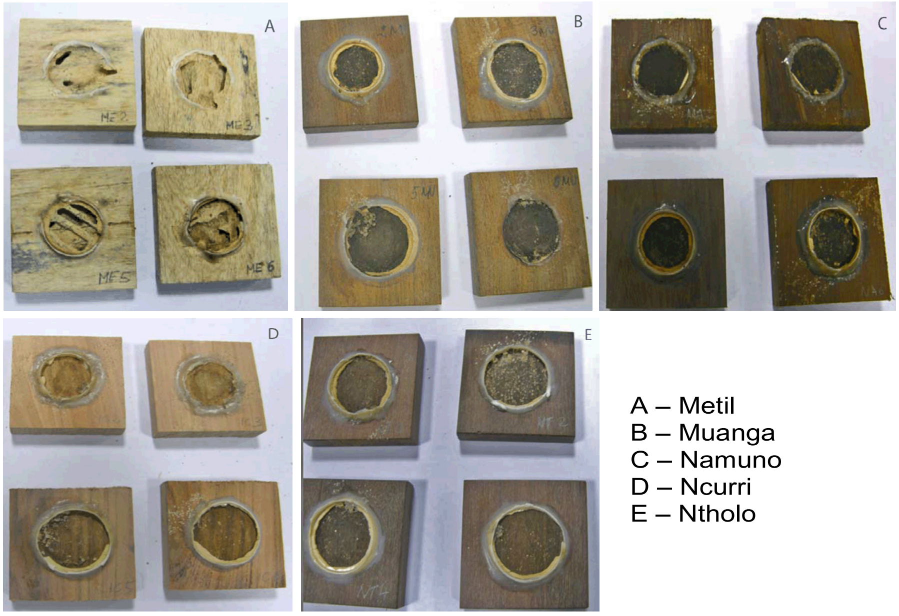

Figure 9 – Appearance of wood after termite test according to standard EN 118

Interestingly, the standard test revealed that the termite survival rate is not necessarily related to durability of the wood species. This is because a lower average percentage of termite death was observed in the test containers with ntholo specimens than in those with muanga, namuno and even ncurri which is classified as moderately durable (**Paper V**). From this, it might be inferred that although ntholo is classified as durable against termite, it can be attacked. In fact, both the termite standard and choice tests showed signs of slight attacks.

The termite choice test showed that among the five tested wood species, metil had higher average ML (61.7%) followed by ncurri (ML equal to 25.2%). Muanga, namuno and ntholo had ML nearly equal to zero percent (**Paper V**). Thus it can be deduced that metil and ncurri constituted the termite's first and second choices, respectively, while muanga, namuno and ntholo were not preferred by the insects.

Although the timbers of muanga, namuno and ntholo were classified as resistant to *R. grassea* and *M. darwiniensis,* **Paper V** recommends more trials of those timbers in tropical areas. Wood which is resistant to one termite species is not necessarily resistant to others found within the tropics (Subriana 1988; Varma et al. 1994).

3.5.5 Field tests

Paper V reports some preliminary data after 18 months exposure in ground contact where heartwoods of muanga, namuno, ncurri and ntholo exposed both in Ultuna and in Marracuene were generally not decayed. However, metil and the reference species (beech and pine sapwood) exposed in Marracuene suffered noticeable decay. The specimens of these three species were rated to failure being severely attacked by termites. Another visual evaluation was carried out six months later on specimens exposed in Ultuna. This revealed high values of decay index of 94.6 for metil, 85 for pine sapwood and 93 for beech. The sapwood of ncurri and ntholo had rates of 48.1 and 43.7, respectively. The heartwoods of muanga, namuno, ncurri and ntholo had equally a significantly low decay rate of approximately 25, indicating higher durability of those species.

The above ground test showed that the sapwood of ncurri was more susceptible to weathering than the heart- and sapwoods of ntholo. Hence, ncurri sapwood had larger MC change in the first months of exposure (**Paper V**). The sapwoods of ncurri and ntholo had larger MC changes than heartwood of ntholo, indicating that they are more hydrophilic than the latter which is less permeable due to its higher extractive content.

The quicker colour change observed among the ncurri sapwood specimens is another factor that supports higher susceptibility to weathering of the species when compared to heart- and sapwood of ntholo (**Paper V**). All exposed specimens showed quicker changes in colour during the first six months of exposure. This is probably explained by the more rapid development of blue stain favoured by higher humidity and rainfall in the first quarter of first year of exposure (October 2008 to February 2009).

It is important to stress that the results obtained from the laboratory methods, including soft rot and basidiomycete fungi and also termite tests, are in line with those obtained from field trials. Hence, the heartwoods of munga, namuno and ntholo had good performance, while metil was the least durable wood in all cases. From this, it might be inferred that timbers of muanga, namuno and ntholo can be recommended for outdoor uses, while that of metil is not if untreated.

3.6 Properties of lesser used timbers and potential end uses

The purpose of this discussion is to assess whether or not the studied lesser used timber species may be viable substitutes for the most commercialised and industrially used timbers in Mozambique. This also considers the possibility for outdoor use of the studied timbers species.

3.6.1 Physical-mechanical properties and potential end uses

As mentioned above, this part is devoted to assess whether or not the studied lesser used timber species might be viable substitutes for the most commercialised and industrially used species in the country. The densities at 12% MC and some mechanical properties of ntholo and metil were compared to those of umbila, chanfuta and jambire in Table 9.

Table 9 – Comparison of ntholo and metil density and mechanical properties with those of well-known wood species (h – Brinell hardness; ⋆ Janka hardness)

Mechanical properties	Lesser used species		Well-known species		
	Metil	Ntholo	Umbila[a]	Chanfuta[b]	Jambire[c]
Density [kg/m^3]	550.6	1023.4	400-700	670	720-990
MOE [N/mm^2]	5800.0	17263.0	8200-9200	13100	13600
MOR [N/mm^2]	54.0	119.2	82-94	108	112
Comp. //[N/mm^2]	26.0	55.7	50-57	-	69
Hardness // grain	4.5^h	7.2^h	5380-7420 N⋆	8229 N⋆	-
Hardness ⊥ grain	1.7^h	4.3^h	4450-6580 N⋆	-	7250 N⋆
I. bend. [kJ/mm^2]	43.1	81.5	57.1	79.2	-

Sources: a) Takawira-Nyenya (2005); b) USDA Forest Service (n.d); c) Lemmens, (2008).

The density at 12% MC for ntholo is higher than those of most well-known timber species from Mozambique. The average density of heartwood of ntholo was 1023.4 kg/m^3. This value is higher than that of umbila which ranged between 400 and 700 kg/m^3. It is also higher than those of chanfuta (670.0 kg/m^3) and of jambire (720-990 kg/m^3). The average density of metil was 550.6 kg/m^3 and is on average lower than of those of umbila, chanfuta and jambire.

The mechanical properties are generally higher in ntholo and lower in metil, when compared to those of umbila, chamfuta and jambire. The average MOE was 17263.0 N/mm^2 in ntholo, while in metil it was only 5800.0 N/mm^2. This value ranged between 8200 and 9200 N/mm^2 in umbila, was 13100 N/mm^2 for chamfuta and 13600 N/mm^2 for jambire. From these data it might be deducted that neither ntholo nor metil cannot be used as direct substitutes for the well-known timber species in Mozambique based on density and mechanical properties.

Nevertheless, ntholo can be used in some structural applications of jambire. In fact, there are some similarities between some properties of ntholo and those of jambire. For example, the MOR of jambire (112 N/mm^2) is somewhat lower than that of ntholo (119.2 N/mm^2). The compression strength of jambire is 69 N/mm^2, while that of ntholo is 55.7 N/mm^2. In addition, ntholo can also serve as a feasible substitute of both chanfuta and umbila in structural applications where strength is a fundamental requirement. The major wood species from Mozambique are referred to as excellent timbers and are mainly used for furniture making, joinery and decorative veneer as well as general construction work and marine use (**Paper I**). Ntholo can also have the mentioned uses, although its heaviness might hinder the common carpentry application such as furniture making.

Metil timber density and hardness seem to favour use such as packaging boxes and plywood. Bosch and Louppe (2008) reported that metil's timber use in Tanzania included local construction, firewood, packaging boxes and plywood. However, with studies reported in **Paper V** was found that metil is perishable and stained easily probably because of the lack of extractives in its very large vessels (Uetimane et al. 2009).

Some published physical and mechanical properties at 12% MC of muanga are as follows: density between 930 and 1030 kg/m^3; MOR between 80 and 106 N/mm^2; MOE between 12600 and 13100 N/mm^2; and compressive strength parallel to grain between 64 and 73 N/mm^2 (Lumbile and Oagile 2008). For namuno, the density at 12% MC was 1200 kg/m^3 and some of mechanical properties were 126 N/mm^2 for MOR, 14810 N/mm^2 for MOE and 73 N/mm^2 for compressive strength parallel to grain (Lemmens 2006). Most of these values of both muanga and namuno are in the same range as those for ntholo. Thus, it is possible that both muanga and namuno might be used in the same application as ntholo.

3.6.2 Natural durability and possible outdoor uses

Section 3.5 presented and discussed the results of studies on natural durability of the five studied wood species for possible outdoor applications through laboratory and field tests. This section presents the main inferences drawn from the results that can be used for recommendations for outdoor uses of the studied wood species.

The heartwoods of namuno, muanga and ntholo were very durable to fungal attack by soft rot, brown and white rots and termite attack. The same species also had good performance in field tests. Therefore they can be considered recommended for outdoor uses even when untreated. Thus, metil was classified as non durable to any of the considered hazards. In this way, metil is not recommended for exterior uses unless treated with an appropriate timber protective product. The timbers of namuno, muanga and ntholo might be used for outdoor wooden structures such as benches and tables in public sites as gardens and amusement parks. They might also be used in playgrounds in various applications including swing seats, goal posts, balances and other play structures.

4 Concluding remarks

The present study constitutes an attempt to promote some lesser abundant but overlooked timber species from Mozambique through providing trustworthy data about physical and mechanical properties and natural durability. The study includes an extensive review to describe the timber sector in Mozambique and discuss the present logging system. The main findings stress the fact that untapped forests from which commercial-sized well known timber species can be obtained are becoming rarer in Mozambique. Therefore, other timber resources, including lesser used species have to be explored to diversify the timber market in the country. This might contribute to reduce pressure on the well known species by increasing the volume of species extracted per unity area, making harvesting more financially viable.

Studies on some physical and mechanical properties of ntholo and metil with regard to their end uses were conducted. Results indicated that ntholo can be used in applications such as building joinery (doors and windows frames or flooring), tool handles or furniture. Ntholo can also be used in some applications traditionally involving the well known timbers of Mozambique, although its heaviness might hinder the common carpentry application such as furniture making. Metil timber is appropriate for use in applications such as packaging boxes and plywood. It might also be used as timber for some wooden construction. The lesser used timber species muanga and namuno have some physical and mechanical properties which are similar to those of ntholo, i.e. both muanga and namuno might be used in the same application as ntholo.

Studies and modelling of the relationship between wood anatomical characteristics, density and mechanical properties of ntholo through a combined and complementary approach of correlation analysis, simple and multiple regression analysis were carried out. Explorations of the predictability of mechanical properties from wood anatomical features and density were also considered. Results suggested that the variation of all of tested mechanical properties of ntholo sapwood was governed by ground tissue proportions, although only the regression equation of MOE was significant. The heartwood regression equations were not significant. Ntholo density was negatively affected by % of vessel proportion and positively by fibre walls thickness. The capability of ntholo density as predictor of some mechanical properties was poor.

The natural durability of the five lesser utilized wood species for outdoor applications using laboratory and field tests was evaluated. The findings lead to recommendations for outdoor uses of the studied wood species as follows: the heartwoods of namuno, muanga and ntholo were very durable (durability class 1) to fungal deterioration by soft, brown and white rots and termite attacks. These species also had good performance in field trials; therefore they are recommended for exterior uses even when untreated. Metil was not durable (durability class 5) to any of the considered hazards. Thus, metil is not recommended for exterior uses if untreated.

All studied species have a good potential for intensive industrial use. They are abundant, have properties that are suitable for various applications and the majority of them are highly durable. A suggestion that these lesser known species should be promoted in the Mozambican timber market is made. Apart from this study, more research on other lesser used timber species growing in the country's forests should be encouraged in the future. A logical continuation of this study could be some further investigations on the behaviour of wood products made of lesser used species from Mozambique. Examples are floors and internal joineries, construction timber of light wood species and exterior products (decks, garden furniture, panels and timber in water contact). In such project durability tests in tropics would play an important role.

Acknowledgements

Thanks to the Swedish International Development Agency (SIDA) and particularly to its Department for Research Cooperation (SAREC) for funding the research project entitled "Improving Wood Utilisation in Mozambique" in which this study is a part. Thanks also to the Faculdade de Engenharia da Universidade Eduardo Mondlane (UEM) for providing opportunity for my PhD studies in Sweden.

This study was conducted with great support from my supervisor Prof. Nasko Terziev at Department of Forest Products of the Swedish University of Agricultural Sciences (SLU). He kindly helped and shared his deep knowledge of wood science that makes up the basis of this thesis. I therefore want to give him my most sincere thanks.

I would like to thank Prof. Geoffrey Daniel, Dr. Ernesto Júnior, Dr. Ulrika Råberg, Dr. Stig Bardage, Dr. Dinesh Fernando and Ann-Sofie Hansen for help in my studies and laboratorial experiments. My gratitude extends to Gabriella Danielsson and Cecilia Åstrand who welcomed me in the Department with great hospitality.

Further, I would like to thank Prof. Rui Vasco Sitoe who gently invited me to take part in the Project Improving Wood Utilisation in Mozambique. Thanks also to Dr. Carlos Lucas and Prof. Torbjörn Elowson for project coordination and help in administrative matters of my studies.

Thanks to my friend and former schoolmate Tarcísio Buanahagi and his family for support in many ways during my stay in Sweden.

Finally, my special appreciation goes to my wife Ana Paula Muitela who endured guiding our family during my studies.

References

Aguilar-Tovar, D., Moya, R. and Tenorio, C. (2009). Wood color variation in undried and kiln-dried plantation-grown lumber of *Vochysia guatemalensis*. Maderas Ciencia y Tecnologia 11 (3): 207-216.

Alberto, M. M. M. (2006). A Contribuição do sector florestal e faunístico para a economia do país. Direção Nacional de Terras e Florestas. Maputo.

Alteyrac, J., Cloutier, A., Ung, C. H. and Zang, S. Y. (2006). Mechanical properties in relation to selected wood characteristics of black spruce. Wood and Fiber Science 38 (2): 229-237.

Armstrong, J. P., Skaar, C. and Zeeuw, C. (1984). The effect of specific gravity on several mechanical properties of some world woods. Wood Science and Technology 18: 137-146.

Bamber, R.K. and Fukazawa, A., (1985). Sapwood and Heartwood: A Review. Forestry Abstracts 46: 567-580.

Bandeira, S. O., Hatton, J. C., Munisse, P. E. and Izidine, S. (1994). The ecology and conservation of plant resources in Mozambique. In Huntley, B. J., ed. Botanical Diversity in Southern Africa. Pretoria, South Africa, pp. 105-115.

Barany, M., Hammett, A. L. and Araman P. (2003). Lesser used wood species of Bolivia and their relevance to sustainable forest management. Forest Products Journal 53 (7/8): 28-33.

Barnett, J. R. and Jeronimidis, G. (Eds) (2003). Wood Quality and its Biological Basis. Blackwell Publishing Ltd. Oxford.

Bekta, I., Güler, C. and Ba türk, M. A. (2002). Principal mechanical properties of Eastern beech wood (*Fagus orientalis* Lipsky) naturally grown in Andirin North-eastern Mediterranean region of Turkey. TÜBTAK. Turkish Journal of Agriculture and Forestry 26, pp. 147-154.

Bila, A., Pariela F. A. and Puná N. (2004). Mercado interno e externo de produtos florestais e faunísticos: presente e perspectivas. MADER-DNFFB, Maputo. Mozambique.

Borrega, M., Nevalainen, S. and Heräjärvi, H. (2009). Resistance of European and hybrid aspen wood against two brown-rot fungi. European Journal of Wood Products 67: 177-182.

Bosch, C.H. and Louppe, D. (2008) *Sterculia appendiculata* K. Schum. [Internet]. Record from Protabase. Louppe, D., Oteng-Amoako AA. and Brink M. (Eds). PROTA (Plant Resources of Tropical Africa. Wageningen, Netherlands. http://database.prota.org/search.htm. Accessed 21 May 2010.

Boutelje, J. B. and Nilsson, T. (1985). The effect of felling time and felling area, wet storage, tree species and wood density on durability of wood. Part 1: Durability against fungal decay. The Swedish Institute for Wood Technology Research, Stockholm. Report No 73.

Bowyer, LJ, Shmulsky, R, Haygreen, GJ (2003). Forest products and wood science: an introduction, 4th Edition. Blackwell Publishing Company. Iowa.

Chauhan, S. S. and Walker, J. C. F. (2006). Variations in acoustic velocity and density with age, and their interrelationship in radiate pine. Forest Ecology and Mamagement 229: 388-394.

Chirkova, J. Andersons, B., Andersone, I (2009). Study of the structure of wood-related biopolymers by sorption methods, Bio Resources 4 (3): 1044-1057.

Choong, E. T. and Achmadi, S. S. (1991). Effect of extractives on moisture sorption and shrinkage in tropical woods. Wood and Fiber Science 23 (2): 185-196.

Chowdhury, M. Q., Rashid, A. Z. M. M., Newaz and Alam, M. (2007). Effects of height on physical properties of wood of jhau (*Casuarina equisetifolia*). Australian Forestry 70 (1): 33-36.

Comision Panamericana de Normas Tecnicas [COPANT] (1972). Maderas. selección y colección de muestras. Normas Copant, Nº 458: 1-11.

Cuvilas, C. A. (2009). Characterization of Available and Potential Sources of Wood Fuels in Mozambique. The Swedish University of Agricultural Sciences. Department of Energy and Technology. Licentiate Thesis. ISBN 1654-9406;

Direção Nacional de Florestas e Fauna Bravia [DNFFB] (2002). Regulamento da lei de florestas e fauna bravia. Decreto No 12/2002. Lei de Florestas e Fauna Bravia.

Direção Nacional de Terras e Florestas [DNTF] (2006). Relatorio esattistico anual 2005. Direcção Nacional de Terras e Florestas – MINAG. Maputo, Mozambique.

Easton, I. and Wright, D. (1998). Developing a marketing strategy to introduce and market lesser-used timber species. CINTRAFOR News 13 (2), pp. 1-3.

Eaton, R. A. and Hale, M. D. C. (1993). Natural durability. *In* Wood decay, pests and protection, 1[st] Edition. Chapman & Hall, London, pp. 311-318.

Edlund, M. L. and Nilsson, T. (1998). Testing the Durability of Wood. Material and Structure 31: 641-647.

EN 113 (1996). Wood preservatives. Method of test for determining the protective effectiveness against wood destroying Basidiomycetes. Determination of toxic values. European Committee for Standardisation (CEN), Brussels, Belgium.

EN 117 (2005). Wood preservatives. Determination of toxic values against *Reticulitermes species* (European termites) (laboratory method). European Committee for Standardisation (CEN), Brussels, Belgium.

EN 118 (2005). Wood preservatives – Determination of preventive action against *Reticulitermes species* (European termites) (Laboratory method). European Committee for Standardization (CEN), Brussels, Belgium.

EN 252 (1989). Field test method for determining the relative protective effectiveness of a wood preservative in ground contact. European Committee for Standardization (CEN), Brussels, Belgium.

EN 350-1 (1994). Durability of wood and wood-based products – Natural durability of solid wood. Part 1: Guide to the principles of testing and classification of the natural durability of wood. European Committee for Standardization (CEN), Brussels, Belgium.

EN 350-2 (1994). Durability of wood and wood-based products – Natural durability of solid wood. Part 2: Guide to natural durability and treatability of selected wood species of importance in Europe. European Committee for Standardization (CEN), Brussels, Belgium.

ENV 807 (1993). Wood preservatives – Determination of the toxic effectiveness against soft rotting micro-fungi other soil inhabiting micro-organisms. European Committee for Standardization (CEN), Brussels, Belgium.

ENV 12037 (1996). Field test methods for determining the relative protective effectiveness of a wood preservative exposed out of ground contact. Horizontal lap-joint method. European Committee for Standardization (CEN), Brussels, Belgium;

Gambetta, A., Susco, D. and Zanuttini, R. (2004). Determination of natural durability of larch wood (*Larix decidua* Mill.) from the Western Italian Alps. Holzforschung 58 (6): 678-681.

Gnanaharan, R. and Dhamodaran, T. K. (1992). Mechanical properties of rubberwood from a 35-year-old plantation in central Kerala, India. Journal of Tropical Forest Science 6 (2): 136-140.

Gierlinger, N., Jacques, D. Schwanninger, M., Wimmer, R., Hinterstoisser, B. and Pâques, L: E. (2003). Rapid prediction of natural durability of larch heartwood using Fourier trasform near-infrared spectroscopy. Canadian Journal of Forest Research 33: 1727-1736.

Gillah, P. R., Makonda, F. B. S., Ishengoma, R. C., Kadala B. and Kitojo, D. H. (2007). Some physical and mechanical properties of *Uapaca kirkiana*, a lesser-known timber species from Tanzania. Tanzania Journal of Forest and Nature Conservation 76: 94-101.

Green, D. W., Winandy, J. E. and Kretschmann, D. E. (1999). Mechanical properties of wood. *In* Wood handbook - Wood as an engineering material. General Technical Report FPL-GTR-113. Madison, WI: U. S: Department of Agriculture, Forest Service, Forest Products Laboratory, pp. 4–1-4–45.

Gryc, V and Horácek, P (2007). Variability in density of spruce (*Picea abies* [L.] Karst.) wood with the presence of reaction wood. Journal of Forest Science 53 (3): 129-137.

Hernandez, R. E. (2007). Swelling properties of hardwoods as affected by their extraneous substances, wood density and interlocked grain. Wood and Fiber Science 39 (1): 146-158.

Highley, T. L. (1999). Biodeterioration of wood. In Wood handbook - Wood as an engineering material. General Technical Report FPL-GTR-113. Madison, WI: U. S: Department of Agriculture, Forest Service, Forest Products Laboratory, pp. 13–1-13–16.

Ishengoma, R. C., Gillah, P. R., Amartey, S. A. and Kitojo, D. H. (2004). Physical, mechanical and natural decay resistance properties of lesser known and lesser utilized *Diospyros mespiliformis*, *Tyrachylobium verrucosum* and *Newtonia paucijuga* timber species from Tanzania. Holz Roh Werkst 62: 387-389.

ISO 3129 (1975). Wood-Sampling methods and general requirements for physical and mechanical tests.

ISO 3130 (1975). Wood-Determination of moisture content for physical and mechanical tests.

ISO 3131 (1975). Wood-Determination of density for physical and mechanical tests.

ISO 3132 (1975). Wood-Testing in compression perpendicular to grain.

ISO 3133 (1975). Wood-Determination of ultimate strength in static bending.

ISO 3345 (1975). Wood-Determination of ultimate tensile stress parallel to grain.

ISO 3348 (1975). Wood-Determination of impact bending strength.

ISO 3349 (1975). Wood-Determination of modulus of elasticity in static bending.

ISO 3350 (1975). Wood-Determination of static hardness.

ISO 3787 (1976). Wood-Test method-Determination of ultimate stress in compression parallel to grain.

ISO 4469 (1981). Wood-Determination of radial and tangential shrinkage.

ISO 4858 (1982). Wood-Determination of volumetric shrinkage.

ISO 4459 (1982). Wood-Determination of radial and tangential swelling.

ISO 4460 (1982). Wood-Determination of volumetric swelling.

Johnson, G. C., Tornton, J. D., Trajstman, A. C: and Cookson, L. J. (2006). Comparative in-ground natural durability of white and black cypress pines (*Callitris glaucophylla* and *C. endlicheri*). Australian Forestry 69 (4): 243-247.

Josue, J. (2004). Some wood properties of *Xylia xylocarpa* planted in Sabah. Sepilok Bulletin 1, pp. 1-15.

Kollmann, F and Côté, W (1984). Principles of wood science and technology. Volume I: Solid wood. Springer-Verlag, Berlin.

Kord, B., Kialashaki, A and Kord, B. (2010). The within-tree variation in wood density and shrinkage and their relationship in *Populus euramericana*. Turkish Journal of Agriculture and Forestry 34: 121-126.

Lemmens, R. H. M. J. (2006). *Acacia nigrescens* Oliv. [Internet] Record from Protabase: Louppe, D., Oteng-Amoako, A. A. and Brink, M. (Editors). PROTA (Plant Resources of Tropical Africa / Ressources végétales de l´ Afrique tropicale), Wageningen, Netherlands. <http://database.prota.org/search.htm>. Accessed 17th September 2010.

Lemmens, R. H. M. J. (2008). *Milletia stuhlmannii* Taub. In: Louppe, D., Oteng-Amoako, A. A. and Brink, M. (Editors). Plant Resources of Tropical Africa 7 (1). Timbers 1. PROTA Foundation, Wageningen, Netherlands / Backhuys Publishers, Leiden, Netherlands/CTA, Wageningen, Netherlands, pp. 373-376.

Lhate, I., Cuvilas, C. Terziev, N. and Jirjis, R. (2010). Chemical composition of traditionally and lesser used wood species from Mozambique. Wood Material Science and Engineering 5 (3): 143-150.

Lumbile and Oagile (2008). *Pericopsis angolensis* (Baker) Meeuwen. [Internet] Record from Protabase. Louppe, D Oteng-Amoako, A. A. and Brink, M. (Editors). PROTA (Plant Resources of Tropical Africa/Ressources végétales de l´ Afrique tropicale), Wageningen, Netherlands. <http://database.prota.org/search.htm>. Accessed 17th September 2010.

Mantanis, G. I., Young, R. A., and Rowell, R. M. (1994). Swelling of wood. Part I. Swelling in Water. Wood Science and Technology 28: 119-134.

Marzoli, A. (2007) Inventário Florestal Nacional. Direcção Nacional de Terras e Florestas. Maputo, Moçambique.
Ministério de Administração Estatal [MAE] (2005a). Perfil do distrito de Montepuez. Província de Cabo Delgado. Série: Perfis Distritais. Ministério de Administração Estatal, Maputo.
Ministério de Administração Estatal [MAE] (2005b). Perfil do distrito de Mussuril. Província de Nampula. Série: Perfis Distritais. Ministério de Administração Estatal, Maputo.
Ministério de Administração Estatal [MAE] (2005c). Perfil do distrito de Marracuene. Província de Maputo. Série: Perfis Distritais. Ministério de Administração Estatal, Maputo.
Otengo-Amoako, A. A. (ed) (2006) 100 Tropical African timber trees from Ghana. Tree description and wood identification with notes on distribution, ecology, silviculture, ethnobotany and wood uses. Forestry Research Institute of Ghana, Department of Publishing Studies, KNUST, Kumasi.
Onuorah, E. O. (2000). The wood preservative potential of heartwood extracts of *Milicia excelsa* and *Erythrophleum suaveolens*. Bioresource Technology 75: 171-173.
Pliura, A., Yu, Q., Zhang, S. Y., McKay, J., Périnet, P. and Bousquet, J. (2005). Variation in wood density and shrinkage and their relationship to growth of selected young poplar hybrid crosses. Forest Science 51 (5): 472-482.
Poku, K., Wu, Q. and Vlosky, R. (2001). Wood properties and their variations within the tree stem of lesser-used species of tropical hardwood from Ghana. Wood and Fiber Science 33 (2): 284-291.
Pometti, C. L., Palanti, S., Pizzo, B., Charpentier, J. P., Boizot, N. Resio, C. and Saidman, B. O. (2010). Durability of five native Argentine wood species of the genera *Prosopis* and *Acacia* decayed by rot fungi and its relationship with extractive content. Biodegradation 21: 753-760.
Salmén, L. and Burget, I. (2009). Cell wall features with regard to mechanical performance. A review. Holzforschung 63 (2): 121-129
Shashikala, S and Rao, R. V. (2009). Radial and axial variation in specific gravity and anatomical properties of plantation grown *Eucalyptus citriodora* Hook. The Journal of Institute of Wood Science 19 (2): 84-90.
Siau, J. F. (1984). Transport Process in Wood. Springer-Verlag, Berlin Heidelberg.
Simpson, W. and TenWolde, A. (1999). Physical properties and moisture relation of wood. *In* Wood handbook - Wood as an engineering material. General Technical Report FPL-GTR-113. Madison, WI: U.

S: Department of Agriculture, Forest Service, Forest Products Laboratory, pp. 3–1-3–24.

Stamm, A. J. (1964). Wood and cellulose science. Ronald, New York.

Subriana, N. (1988). Studies on the Natural Durability of Tropical Timbers to Termite Attack. International Biodeterioration 24: 337-341.

Suleiman, B. M., Larfeldt, J., Lockner, B. and Gustavsson, M. (1999). Thermal conductivity and diffusivity of wood. Wood Science and Technology 33: 465-473.

Takawira-Nyenya R. (2005). *Pterocarpus angolensis* DC. [Internet]. Record from Protabase. Louppe D, Oteng-Amoako AA and Brink M. (Eds). PROTA (Plant Resources of Tropical Africa. Wageningen, Netherlands. <http://database.prota.org/search.htm>. Accessed 25th March 2010.

Tsoumis, G. T. (1991). Science and technology of wood: structure, properties, utilization. Van Nostrand Reinhold. New York.

Tsunoda, K. (1990). The natural resistance of tropical woods against biodeterioration. Wood Research 77: 18-27.

Taylor, A. M., Gartner, B. L., Morrell, J. J., (2002). Heartwood Formation and Natural durability – a Review. Wood and Fiber Science 34 (4): 587-611.

Uetimane Jr., E. (2010). Anatomy, drying behaviour and mechanical properties of lesser used wood species from Mozambique. The Swedish University of Agricultural Sciences. Department of Forest Products. Doctoral thesis No. 2010:66. ISBN: 978-91-576-7511-8.

Uetimane Jr, E., Allegretti, O., Terziev, N and Söderström O. (2010). Application of non-symmetrical drying tests for assessment of drying behaviour of ntholo (*Pseudolachnostylis maprounaefolia* Pax). Holzforschung 64 (3): 363-368.

Uetimane Jr, E., Terziev, N and Daniel, G. (2009). Wood anatomy of three lesser known species from Mozambique. IAWA Journal 30 (3): 277-291.

USDA Forest Service (n.d.). Wood technical fact sheet. Forest Products Laboratory- One Gifford Pinchot Drive, Madison, WI 53705-2398.

Usta, I. (2003). Comparative study of wood density by specific amount of void volume (porosity). Turkish Journal of Agriculture and Forestry 27: 1-6.

Van Acker, J., Militz, H., and Stevens, M. (1999). The significance of accelerated laboratory testing methods determining the natural durability of wood. Holzforcshung 53 (5): 449-458.

Varma, A., Kolli, B. K., Paul, J., Saxena, S. and König, H. (1994). Lignocellulose degradetion by microorganisms from termite hills and termite guts: A survey on the present state of art. Microbiology Review 15: 9-28.

Verheyden, A., Gitundu, K., Beeckman, H. and Koedam, N. (2004). Growth rings, growth rings formation and age determination in mangrove *Rhizophora mucronata*. Annals of Botany 94, pp. 59-66.

Wieringa, J. J. (1999) Monopetalanthus exit. A systematic study of Aphanocalyx, Bikinia, Icuria, Michelsonia and Tetraberlinia (Leguminosae, Caesalpinioidae). Wageningen Agricultural University 99 – 4: 1-320

Willeitner, H. and PeeK, R. D: (1997). The natural durability story. International Research Group on Wood Preservation, Stockholm.IRG Doc. IGR/WP 97-20119.

Winandy, J. E. (1994). Wood properties. In: Arntzen, C. J. ed. Encyclopedia of Agricultural Sciences. Orlando, FL: Academic press. Volume 4, pp. 549-561.

Worbes, M. (1995). How to measure growth dynamics in tropical trees – a review. IAWA Journal 16: 337-351.

Yamamoto, K. and Hong, L. (1994). A laboratorial method for predicting the durability of tropical hardwoods. Japan Agricultural Research Quarterly 28 (4): 268-275.

Yang, J. L. and Evans, R. (2003). Prediction of MOE of eucalypt wood from microfibril angle and density. Holz als Roh-und Werkstoff 61: 449-452.

Zziwa, A., Kaboggoza, J. R. S., Mwakali, J. A., Banana, A. Y., and Kyeyune, R. K. (2006). Physical and mechanical properties of some less utilised tropical timber tree species growing in Uganda. Uganda Journal of Agricultural Sciences 12 (1): 29-37.