Anatomy, Drying Behaviour and Mechanical Properties of Lesser Used Wood Species from Mozambique

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Abstract

The study provides an overview of Mozambique timber sector, descriptive and comparative wood anatomy, drying experiments and interrelationships between mechanics, density and anatomical features of lesser used species from Mozambique. Exhaustive literature review described the timber sector as dominated by few hardwood species selectively harvested from a forest containing 118 potential wood species. The survey discussed the need to revert the current situation by proposing studies on lesser used timbers to enlarge the resource base and ensure sustainable logging practices. Afterwards, based on growing stock reported in the forest inventory, three lesser used timbers namely ntholo (*Pseudolachnostylis maprounaefolia* Pax), metil (*Sterculia appendiculata* K. Schum) and muanga (*Pericopsis angolensis* Meeuwen) were selected and subjected to descriptive and comparative wood anatomical studies aiming to understand their structure with regard to prospective end uses. Classical methods of wood sectioning and both light microscopy (LM) and scanning electron microscopy (SEM) were used. The results showed that ntholo and muanga are characterized by diffuse porosity, indistinct growth rings, 18 vessel/mm^2, extractives in heartwood vessels, ray width (1-3 cells), % fibre proportion (ntholo 57%; muanga 58%). This set of anatomical features typifies dense timbers with recognized strength and good natural durability. Metil has shown wood structure characterized by very wide vessels without extractives recorded in low density (< 5 vessels/mm^2), ground tissues dominated by thin-walled axial parenchyma (50-61%) and fibre proportion (17-27%). Metil wood anatomy is typical for light timbers with poor natural durability. Nevertheless, metil timber seems easy to impregnate with wood preservatives as demonstrated by the high uptake of 463 kg/m^3. In addition, the study carried out drying experiments on ntholo boards aimed to assign adequate drying schedule. The experiment was conducted in two stages, i.e. non-symmetrical drying tests (NSD) and laboratory batch kiln drying (LBK). NSD was intended to select provisional schedule and LBK to test the performance of the selected schedule based on European standards. The results from NSD assigned provisional schedule (T6-D2) corresponding to other tropical timbers with similar drying behaviour. The LBK lasted 266 h and ensured standard quality drying described by 8.9% final moisture content, a gradient of 1.2% and 1.2 mm of casehardening. Minor deformations were recorded and twist was the largest with an average of 3.4 mm. However, in general, the drying experiment can be regarded as successful since it provided background for industrial drying. Finally, the study determined ntholo timber mechanics and thereafter examined interrelationships with density and anatomical features of ntholo through correlation and regression analysis. The results show that ntholo is a very dense timber with high mechanical strength in comparison to well known timbers. Correlation analysis revealed fibre length as 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. All tested properties of ntholo sapwood seemed to be influenced mainly by ground tissue proportions, while heartwood properties were described by more leveled anatomical predictors. The regression analyses show that both ntholo sapwood and heartwood densities are poor predictors for the tested mechanical properties, although may provide rough indication of tested properties given the observed correlations. The integrated analysis of results from the timber sector review, wood anatomy, drying behaviour and mechanical properties are expected to form a reliable background for a successful utilization of the relatively lesser explored timbers from Mozambique.

Keywords: drying schedule, mechanical properties, Mozambique, non-symmetrical drying test, tropical hardwood species, wood anatomy

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Dedication

To the memory of my beloved sister Francisca Gisela Uetimane

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

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

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

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

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

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Abbreviations

DNFFB	Direcção Nacional de Florestas e Fauna Bravia
FSP	Fibre saturation point
IAWA	International Association of Wood Anatomists
LBK	Laboratory batch kiln
LM	Light microscopy
MC	Moisture content
NSD	Non-symmetrical drying
RLS	Radial longitudinal section
SEM	Scanning electron microscopy
TLS	Tangential longitudinal section
T6-D2	American coding system of moisture based drying schedules
TS	Transverse sections

1. INTRODUCTION

Timbers from Mozambique are largely known to produce quality hardwood items in the international arena. They are selectively harvested from the species rich Miombo forests across the country. The more vigorous and productive forests grow in the tropical range of central and northern regions of Mozambique. The southern part which also includes the subtropical region of Maputo province is naturally less forested and the few existing logging areas are nearly depleted (Marzoli 2007). Therefore, the wood consumers from south, especially from Maputo, are competing with Mozambican wood importers in central and northern areas. Nowadays, both logs and sawn wood are transported daily by road to Maputo in journeys beyond 2000 km.

Apart from small carpentries, both logging and sawmilling are the main activities in the country timber sector and provide employment in many rural areas (Eureka 2001). Like in other African countries, Mozambican forests are subjected to many problems such as illegal logging, lack of management plans, highly selective logging and shortened felling cycles. Thus, in recent years the long term sustainability of forest exploitations was under scrutiny (Ogle & Nhantumbo 2006).

As response, the Mozambique government decided to promote forest concessions over the ineffective annual simple logging license regime. The assumption is that concessionaires are allowed to exploit the forest for a renewable period of 50 years under a detailed management plan that include replanting, establishment of local wood processing facilities, construction of social infrastructures and many other benefits for the local communities. The search for alternative wood species for the over exploited timbers is highly prioritised in the management plan (DNFFB 1999).

However, the search for substitutes/alternatives wood species is dependent on assessment of their properties and subsequent comparison with the well known marketed species. Other African countries have already started to look for alternative wood species. Examples are reports from Tanzania (Gillah et al. 2007), Uganda (Zziwa et al. 2006), and Ghana (Otengo-Amoako 2006; Poku et al. 2001). In Mozambique, the present study represents an early attempt on this matter. The study reviewed exhaustively the timber sector, carried out anatomical descriptions, performed drying experiment to assign suitable drying schedule as well as determined and analysed relationships between mechanical properties, density and anatomical features of lesser used wood species from Mozambique. The choice of species was based on the growing stock reported in the forest inventory (Marzoli 2007). The chosen species are ntholo (*Pseudolachnostylis* *maprounaefolia* PAX), metil (*Sterculia appendiculata* K. Schum) and muanga (*Pericopsis angolensis* Meeuwen). The study devoted more work on ntholo due to its relative high growing stock in comparison with other lesser used species. The approach was to compare the determined properties of lesser used with the well known species to enable end use assessment.

1.1 Wood species from Mozambique – brief overview

Like other natural tropical forests, the flora of Mozambique is largely composed of hardwoods including some endemic species. In fact, African forests consist of 99% hardwoods (Bowyer et al. 2003). A lesser amount of wood is supplied from plantations with fast growing species. The genus *Pinus* represents the majority of planted softwoods in Mozambique, whereas eucalyptus is the most planted hardwood.

However, despite a relative fast growth of the referred species, forest plantations are still expanding and cannot meet the current demand. Therefore, the country's natural forests are still the only source of wood supplying native hardwoods for both domestic and international market. The highly selective logging along with slow growth of the natural forest alerted authorities to promote fast growing wood species to meet the ever increasing demand in the coming years.

Fig. 1. Tropical native forest stand dominated by endemic trees of *Icuria dunenis* Wieringa (Matibane forest Reserve, Nampula, Mozambique).

Notorious evidence is the overexploitation subjected to wood species such as umbila (*Pterocarpus angolensis* DC), chanfuta (*Afzelia quanzensis* Welw) and jambire (*Millettia stuhlmannii* Taub.). This situation suggests not only depletion of country´s finest timbers, but also loss of biodiversity, natural

heritage as well as imbalanced ecosystem. The current logging trend threatens to reach forest reserves and other protected areas with endemic species in search for the most known and precious timber species.
Table 1 summarises the proportion of wood exploitation of 118 industrially available wood species listed in the forest guidelines in year 2004.

Table 1. Proportion of wood exploitation by species (data from 2004).

Wood species	% total exploited wood
Umbila	30
Chanfuta	30
Jambire	19
Rest of species	21
Total	100

Source: DNFFB (2005)

The figures from Table 1 show that umbila, chanfuta and jambirre account together 79% of the total timber national production. Nevertheless, the high diversity of wood species in the tropical natural forest represents an opportunity to search for alternative wood species with comparable properties to the over exploited. It is expected that prospective wood species will increase available options in the timber markets as well as ensuring sustainable logging regime.

1.2 Tree descriptions of lesser known wood species

1.2.1 Pseudolachnostylis maprounaefolia PAX (Euphorbiaceae)

Trees of this species are mainly small, 5 to 10 m tall, with semi-circular crowns. The trunk diameter is often 30 cm with brown and cracked bark. The species grows naturally in habitats ranging from Central to East tropical Africa. In Mozambique, ntholo trees grow on the northern Save River especially in plateau areas of open forest with sandy-clay and frequently yellow soils (Marzoli 2007; Gomes e Sousa 1968).

1.2.2 Pericopsis angolensis (Baker) Meeuwen (Leguminosae)

Muanga is a fast growing deciduous tree with a fairly open crown, 20 m tall, trunk diameters of 35 to 60 cm. The trees are mostly medium to large sized, with pale grey to whitish smooth bark and irregularly-shaped thin pieces peeling off the lower trunk. Muanga is a common tree in the *Brachystegia* woodlands and wooded grassland in altitudes ranging from 500 to 1650 m, growing naturally in Congo Kinshasa, Zimbabwe, Tanzania and

Mozambique. Muanga resembles *Pericopsis elata* growing in West Africa (Hyde & Wursten 2008b; Dirninger 2004)

1.2.3 Sterculia appendiculata K. Schum (Sterculiaceae)

Metil is a deciduous species with unbranched trunks (diameter > 50 cm) and is up to 40 m tall. The only branching is observed close to the crown. The bark is smooth, pale to yellowish grey and the young branchlets have dense woolly, rusty-yellow hairs. Natural distribution of this species is Malawi, Mozambique, Tanzania and Zimbabwe with the trees growing mainly in coastal and riverside forests (Hyde & Wursten 2008a).

1.3 The importance of wood anatomy for better timber utilization.

The knowledge of wood anatomy is widely regarded decisive in understanding wood properties and behaviour (Bowyer et al 2003; Barnett & Jeronimidis 2003; Dinwoodie 1981). However, wood cellular morphology experiences great variability within and between tree species caused mainly by growing conditions and genetic factors. Obviously, there is no wood structure capable of accommodating every end use. This is why foresters and tree breeders strive to produce trees with predefined features targeting specific end uses. On the other hand, wood technologists need to understand wood anatomy to ensure successfully wood modification for improved timber use, e.g. removing extractives from vessels before treating wood with preservatives to prolong life service. Reliable timber identification precedes full anatomical examinations in order to characterise peculiar cell types of certain wood species. Modeling of fluids and water flow in wood requires understanding interconnection of cells by mean of pits and vessel perforations (Siau 1984; Dinwoodie 1981). Even density which is the most used parameter to estimate wood strength is always related to wood structure. According to Dinwoodie (1981), density is related to the relative proportions of the various cell types and more specifically reflects their absolute wall thicknesses.

1.4 Wood drying in Mozambique

In Mozambique, very few sawmills perform conventional kiln drying. Air drying is often and unsystematically used instead. The top three species (umbila, chanfuta and jambire) are intrinsically not prone to major drying defects (Bunster 1995). The same does not hold true for the majority of species growing in Mozambique, especially the lesser used species. The lack of drying routines have been sustained by the fact that most of the country finished wood products are consumed internally and rarely exported to the quality demanding international markets. Due to the decline of the fine timbers growing stock, sawmills will have to process wood species relatively prone to drying defects such as the lesser used species.

In temperate zone countries, sawmills process few species but in large amounts that are enough to fill large kilns whereas in the tropics it is necessary to gather different species to fill the kiln. Common practices include grouping wood species with similar drying behaviour and thereafter kiln dry them under the same schedule. This is generally achieved through mathematical models correlating density with other properties such as moisture content, shrinkage and drying temperature (Simpson & Baah 1989; Hisada & Sato 1980). Using this approach, drying times of 650 tropical timbers were statistically modeled (Simpson & Sagoe 1991; Ma 1975). Nevertheless, the referred drying approach does not monitor susceptibility of timber to drying stresses and resulting drying defects.

A relatively new approach called non–symmetrical drying (NSD) assessing diffusion coefficient and residual strain of dried boards has been used to describe drying behaviour of lesser known tropical timbers (Allegretti & Ferrari 2007; Aguiar & Perré 2000; Brandao & Perré 1996). In the present study, NSD tests were applied to set ntholo drying schedule. Under the same relative humidity (25%), but in two trials with different temperatures (45°C and 60°C), small clear sap-heartwood specimens were subjected to NSD tests which enabled estimates on drying rates through diffusion coefficient and corresponding deformations on real time measurements using displacement transducers. The method allowed selection of a provisional drying schedule for ntholo by comparison with other species with similar drying behaviour under NSD.

1.5 Objectives of the study

The objectives of the present study are as follows:

1. Review Mozambique timber sector. Explore the needs to identify prospective alternative wood species to widen choices in terms of timber species. Discuss selection of lesser used wood species. Draw baseline for further studies on wood properties of the selected lesser used species from Mozambique;

2. Describe wood anatomy of three lesser known wood species from Mozambique (ntholo, muanga and metil) and discuss anatomical

structures in relation to wood properties. The study also addressed comparative wood anatomy of the three species;

3. Assessment of ntholo drying behaviour through diffusion coefficient and residual strain intended to determine a suitable drying schedule. Test the suitability of the provisional drying schedule through standardized methods in a laboratory batch kiln to simulate industrial kiln drying;

4. Modeling the relationships between wood anatomical features, density and mechanical properties of ntholo through a combined and complementary approach of correlation analysis, multiple and simple regression analysis. Assess the predictability of mechanical properties from wood anatomical features and density.

2. MATERIALS AND METHODS

An extensive review was carried out to describe the situation of Mozambique commercial wood species, discussing primarily the dilemma of the current logging regime. Various documents such as wood species fact sheets along with official reports from the Ministry of Agriculture were used to survey the country timber sector (Paper I). The remaining part of the study was merely experimental and included description of anatomical features, wood drying trials and analyzing relationships between anatomical features, density and mechanical properties. The applied procedures for the experimental studies are described below.

2.1 Sampling and trees habitat

The sampled trees of ntholo were felled from natural forest with mixed species located in the northern province of Cabo Delgado, about 60 km from the central Montepuez, Mozambique. The exact geographical coordinates are S12º 15´39.5´´;E 39º11´57.4´´; altitude 376 m. The sampled stand grew under semi-arid, sub-humid and dry climate. The annual average precipitation ranged from 800-1000 mm, while annual temperatures are 20 to 25ºC on average (Mozambique Ministry of State Administration 2005).

In total, five trees of ntholo were randomly harvested from their natural growing stand based on recommended procedures for anatomical, physical and mechanical property studies *(COPANT* 1972). Samples of both muanga and metil were collected from a sawmill in the same province (Cabo

Delgado) and according to the sawmill manager the trees of these two species were harvested from nearly the same natural stand of ntholo (Paper II). Anatomical descriptions were based on samples taken from butt logs at breast height.

2.2 Wood anatomy of three lesser used species from Mozambique

2.2.1 Microscopy and image analyses

The anatomical observations and descriptions were carried out using either light microscopy (LM) or scanning electron microscopy (SEM). The description of anatomical features employed terminology and procedures from IAWA Hardwood List (IAWA Committee 1989). For LM examination, small wood blocks were boiled in solution of 10% glycerin for 4 h. Then, the samples were repeatedly rinsed and left in water overnight. However, some blocks were still hard to section. The softened blocks were sectioned (20-40 *μm* thick) using a Leitz sliding microtome. Afterwards, some sections were stained either with 1% lactophenol blue (longitudinal sections) or 1% safranin (transverse sections).

Image-Pro Plus software was used to measure quantitative features such as vessel density, vessel lumina diameter, number of rays, average tissue proportions, vessel element length including the tails and fibre length. The measurements of both vessel element and fibre length was possible after the samples were delignified and macerated by treatment in a 1:1 mixture of 100% acetic acid (CH_3COOH) and H_2O_2 under 60ºC for 18 h (Wise et al. 1946).

The SEM allowed examination of features like vestured pits and needle-like crystals. Therefore, semi-thin sections (i.e. TS, TLS, RLS) were air-dried, mounted on stubs, coated with gold and observed using a Philips XL30 ESEM at 15 kV (Daniel et al. 2004). The described features from both LM and SEM were used to discuss potential wood properties and also anatomical features that can hinder wood performance in service (Paper II).

2.3 Ntholo wood drying experiments

2.3.1 Non-symmetrical drying tests and laboratory batch kiln drying

This experiment (Paper III) was aimed to select a provisional drying schedule for ntholo by using a non-symmetrical drying test (NSD). Thus, (radial and tangential) sides of ntholo wood specimens were insulated using aluminium sheets leaving only one free surface (120×150 mm). Ntholo specimens were placed on a lateral support defining the reference plan and subsequently attached to displacement transducers to allow continuous measurement of sample deflections (negative or positive) (Fig. 4, left) which were expressed as reciprocal of curvature radius (1/r).

Finally, the specimens were dried in a climatic chamber by two constant climates described by identical relative humidity (RH) of 25%, but maintaining 45 and 60°C dry-bulb temperature (Fig. 4, left). As described earlier, the objective of this experiment (NSD) was to assign a provisional ntholo drying schedule from a set of already known wood species according to their diffusion coefficient *D* and residual strain (Allegretti & Ferrari 2007).

The NSD test results allowed provisional assigning of the American schedule T6-D2 (Denig et al. 2000; Paper III). The referred schedule was further tested in kiln batch under laboratory conditions. A batch kiln (2 m^3) was used to dry 28-mm-thick ntholo boards to assess the suitability of the assigned drying schedule generated from NSD tests (Fig. 4, right).

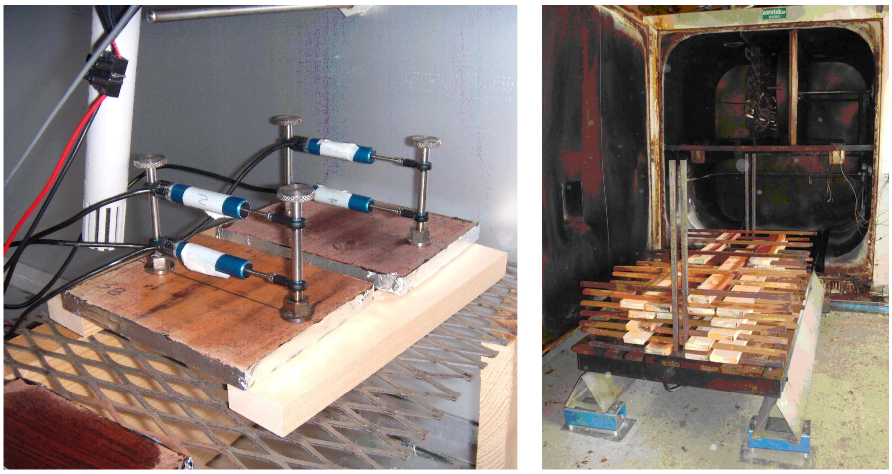

Fig. 4. Insulated specimen and attached transducers inside the climatic chamber during NSD tests (left) and laboratory batch kiln drying trial (right).

2.3.2 Assessing ntholo drying quality under provisional schedule

The performance of the selected provisional schedule (T6-D2) was assessed by performing quality control of the dried boards. The drying quality was mainly monitored through parameters such as final moisture content (MC) profiles (variations within and between boards), relative check area, casehardening and board deformations. The relative check area was calculated according to Bekele (1994), but the other mentioned parameters were assessed according to European standards (EN 14298 2004; EN 13183-1 2003; ENV 14464 2003).

2.4 Relationships between wood anatomical features, density and mechanical properties of ntholo

2.4.1 Sampling and physico-mechanical properties

Twenty one clear samples (20×20×400 mm) representing sapwood and 21 samples consisting of heartwood were prepared. The samples were taken from five ntholo trees regardless of their location within the logs. The samples were prepared according to procedures outlined by International Organization for Standardization (ISO 3129: 1975). The tested physico-mechanical properties are density at 12% MC (D_{12}), Brinell static hardness (B_H), compression strength (CS) (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 known/used timber, the tested properties of ntholo were compared to the well known timbers to enable end-use assessment.

2.4.2 Anatomical descriptions

In all tested specimens, small blocks were taken close to the failure point and then subjected to treatments to obtain anatomical slides as described in Paper II. Additionally, in this study the small blocks were repeatedly autoclaved to soften them prior to sectioning. The characterised anatomical features are fibre dimensions/morphology (length, wall thickness and diameter), vessel features (diameter and number of vessels/mm^2) and average ground tissue composition (%fibres, %parenchyma including rays and %vessels).

2.4.3 Statistical analyses

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 regression (PLS) 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 sought relationships are represented as follow: Y = X1 + X2 + X3 + X4 + X5 + X6 + X7 + X8

Where Y dependent variables = physical or mechanical properties ($D_{12,}$ MOE, MOR, BH and CS) and X-independent variables: X1 = %Fibres; X2 = %Vessels; X3 = %Parenchyma tissue (rays included); X4 = Number of vessels/mm^2; X5 = Vessel diameter; X6 = Fibre length; X7 = Fibre diameter; X8 = Fibre wall thickness.

The predictive abilities of the generated models were assessed through the leave-one out cross validation method. Simple linear regression was used for practical reasons by taking ntholo density as independent variable to predict each mentioned mechanical property (Paper IV).

3. RESULTS AND DISCUSSION

3.1 Mozambique timber sector - overview

The situation of the Mozambique timber sector is extensively presented in Paper I. The study described present situation of the most harvested and used timbers. It was shown that the timber sector in Mozambique ranks amongst the most important of the national economy. However, poor forest management and the extremely selective logging system are likely to impair the sector. Visible negative consequences resulting from the current forest exploitation regime is the early abandoning of highly forested areas after an average logging period of 5 years once the known wood species are nearly depleted. This scenario suggests rapid forest depreciation, loss of employment for rural inhabitants as well as the country´s failure to increase exportation of one of the most important natural resources. Paper I addressed the need for research on properties of lesser known/used species. The pointed benefits include easy marketability, increased logging productivity and forest value and more consumable/exportable timber species. Encouraging findings from Paper I are mainly framed in the fact that some most used timbers have comparable density with the lesser known species (Table 2).

Table 2. Comparison of density of lesser- and well known wood species from Mozambique.

Density (kg/m^3)			
Lesser used timbers		Well known timbers	
Muanga	Metonha	Chanfuta	Umbila
865	780	670	590

Density is known to be associated with many wood properties, especially strength. The reported similarities on density and probably other properties between lesser used and well known timber species allowed setting the baseline for further studies. The densities of both muanga and metonha are relatively higher than the well known timbers (Table 2). Therefore, it is expected that some lesser known wood species might be used as alternatives timbers, especially in applications where strength is a key characteristic. However, research on other important properties such as wood anatomy to understand the structure and suitable drying schedules will ensure better utilization of the promoted timber species.

To ensure sustainability on the proposed approach of species diversification, the study emphasized research on overlooked species with considerable growing stock reported by Marzoli (2007) in the forest inventory. The study exposed concerns emerging from the fact that continued selective logging could accelerate timber depletion increasing the risk of harvesting immature trees. A deductive point drawn from Paper I is that the future national timber harvesting quota should be distributed for many species including the lesser used ones. This approach would relieve pressure over the well known timbers and ensure sustainable forest management.

3.3 Wood anatomy of three lesser known/used wood species

Paper II is entirely dedicated to describe the anatomical features of three lesser used timber species from Mozambique, viz. *Sterculia appendiculata, Pericopsis angolensis* and *Pseudolachnostylis maprounaefolia*. The study discusses the implication of the structure in connection to the wood properties. The results of anatomical characterizations revealed that all three species have diffuse porosity (Fig. 5). Generally, both ntholo and muanga share many similar anatomical features such as indistinct growth rings; distinct heartwood; straight grain; fibre composition (57% ntholo; 58% muanga), vessel density (18/mm^2); vessel outline (rounded shape); extractives in the heartwood vessels; diameter of vessels (ntholo-108 µm; muanga-131µm); ray features such as number of rays as seen from TLS (muanga: 4-14/mm; ntholo 5-15/mm), ray width (1-3 cells) and fibre length (ntholo has 2025 µm and muanga 2156 µm). A different structure characterised metil wood anatomy: indistinct heartwood, a low vessel density (< 5 vessels/mm^2), vessels with either rounded or oval shapes, no extractives, average vessel diameter more than twice (371 µm) as wide as both ntholo and muanga vessels, high percentage volume of thin-walled axial parenchyma tissue

(53%), thick-walled fibres (22%) and ray width up to 17 seriate. Figure 5 shows typical transverse sections of the three wood species.

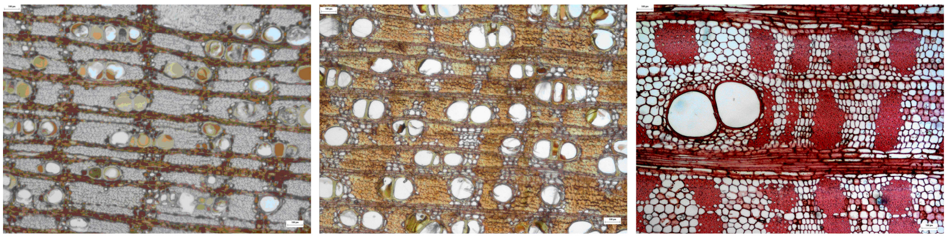

Fig. 5. Transverse sections of the three lesser used wood species.

The study discussed the implications on some wood properties. Therefore, properties such as density, treatability, drying and natural durability were tentatively predicted from the wood structure and confirmed by laboratory measurements (Table 3; Paper 2).

Table 3. Measured and predicted wood properties.

Mean values of some wood properties and drying	**Ntholo**	**Muanga**	**Metil**
Density (12% MC) (kg/m^3)	Very high (950)	Very high (941)	Low (448)
Treatability (heartwood retention) (kg/m^3)	Extremely difficult (43)	Difficult (110)	Easy to treat (463)
Drying	Slow (D = 2.49E-10 m^2/s)	Slow*	Fast*
Natural durability	Very durable*	Very durable*	Slightly non-durable*

* Predicted properties; D- Diffusion coefficient measured through non-symmetrical drying test at 60°C and 25% relative humidity.

The similarity of some anatomical features between muanga and ntholo such as presence of extractives in heartwood vessels and high fibre composition justifies the predicted and confirmed high density as well as slow drying rate for ntholo. The study inferred the same drying behaviour for muanga since timber species containing extractives and high density have usually long drying time. On the other hand, the presence of extractives is generally associated with the predicted natural durability and makes most timbers difficult to treat for many liquids including wood preservatives. The lack of extractives along with low density observed in metil timber suggest high susceptibility to biodegradation, fast drying rate, but relatively easy to impregnate with wood preservatives to prevent deterioration if the timber is to be used in outdoor applications.

3.4 Ntholo wood drying experiments

3.4.1 Application of NSD tests for allocation of provisional schedule

Ntholo was the species prioritized for further studies due to its abundant growing stock in comparison with muanga and metil (Paper II). Therefore, ntholo boards were subjected to drying experiments aimed to allocate a suitable drying schedule. This study is addressed in Paper III. The experiment was carried out in two stages: (i) NSD tests aimed at assigning provisional drying schedule; (ii) laboratory batch kiln drying to assess the performance of the provisional schedule based on NSD tests. For better understanding of NSD tests it is important to stress that during these tests, the boards experience physical and mechanical behaviour corresponding to boards of double thickness subjected to symmetrical drying (SD). In SD the core of the board and the surface correspond respectively to the insulated face and the free surface under NSD conditions. The drying time of the two boards is the same, but in SD the internal stresses develop without some apparent deformations due to the symmetry of the stress apart from that caused by wood anisotropy. The relationship between SD and NSD tests in terms of stress development is tentatively shown in Figure 6.

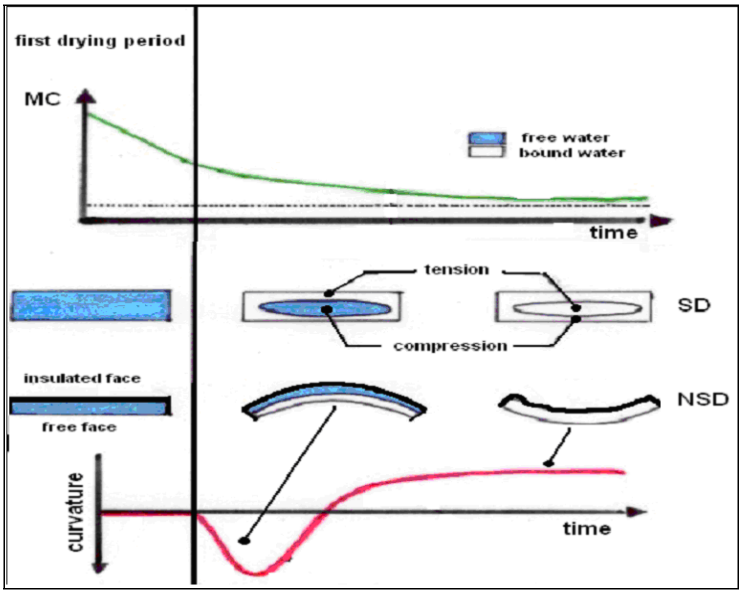

Fig. 6. Stress development during drying (modified after Aguiar & Perré 2000).

NSD tests allowed estimations of diffusion coefficient (*D*) of 2.49 $\times 10^{-10}$ m^2/s and a residual strain of 0.021 /mm for ntholo. Thus, in comparison with other tropical hardwoods dried under NSD with D plotted against residual strain, ntholo was classified as easy, but as a slow drying species similar to hardwoods cherry and niangon (Fig. 7). Ntholo therefore showed similarity to species in terms of drying behaviour with known drying schedule (American schedule T6-D2, Denig et al. 2000) (Paper III). Therefore, the drying schedule T6-D2 was provisionally allocated to ntholo and subsequently tested in a laboratory batch kiln.

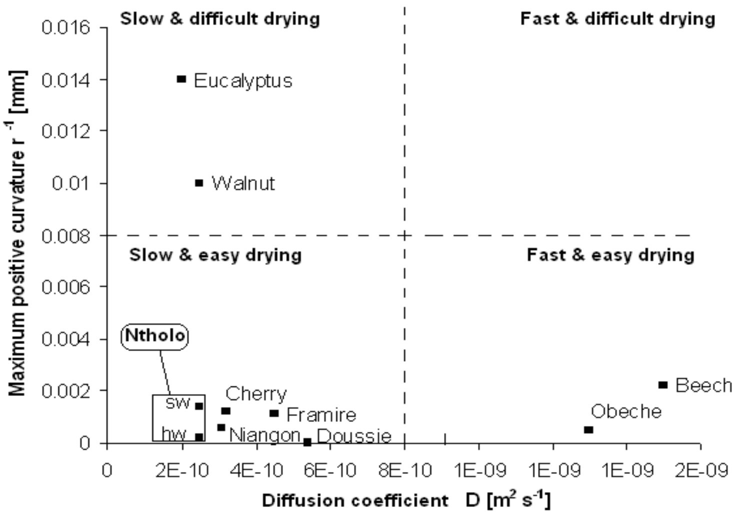

Fig. 7 Species disposition based on drying behaviour in terms of drying rate (X axis) and final deformation (Y axis) (sw –sapwood; hw – heartwood).

3.4.2 Testing the provisional schedule in laboratory batch kiln drying

The selected drying schedule (T6-D2) was implemented on ntholo boards of 28 mm thickness. The drying process lasted 266 h and the schedule was slightly modified as follows (Fig. 8):

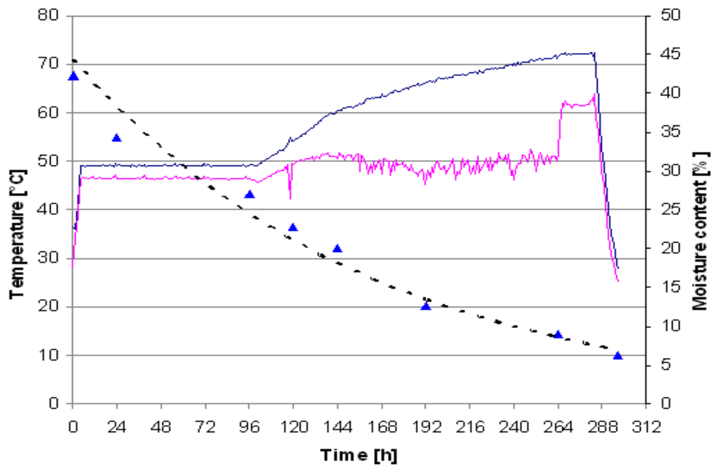

Fig. 8. Batch kiln drying test with small modifications of the provisional schedule T6-D2. (blue line – dry bulb temperature, red line-wet bulb temperature); dotted line – MC).

The drying schedule was monitored by board moisture content loss. In the beginning, both dry and wet-bulb temperatures were set as originally prescribed in the selected schedule (Table 1, paper III). Afterwards, somewhere in the transition period between the second and third drying stage notable stress was detected through prong tests. The recorded stresses on boards prompted adjustments of the tested schedule, i.e. the second part was made notably milder than the original parameters. Other minor adjustments such as small temperature differences during drying are related to batch kiln control operations. Table 4 lists the assessed quality features of the dried boards under the provisional assigned schedule.

Table 4. Quality control of ntholo boards dried under T6-D2

Assessed quality features	**Mean**	**Sd***	**Min**	**Max**
Final MC, board weight (%)	6.3	4.6	2.9	12.3
Final MC, samples (%)	8.9	0.9	7.4	10.6
Moisture gradient (%)	1.2	0.5	0.4	1.6
Gap (mm)	1.2	0.4	0.5	1.9
Bow (mm)	1.0	0.8	0.0	2.0
Crook (mm)	1.1	0.6	0.0	2.0
Twist (mm)	3.4	2.3	0.0	8.0
Cup (mm)	0.6	0.3	0.0	1.0
Relative check area (%)	0.45	1.1	0.0	4.4
Relative end check area (%)	0.95	2.9	0.0	10.2

*Sd-standard deviation

In general, based on quality criteria of European drying standards (EN 13183-1 2003; EN 14298 2004; ENV 14464 2003) ntholo boards showed standard and quality characteristics under T6-D2. The average final MC of the entire board was 6.3%, i.e. lower than the targeted 8% final MC, but still in the range (8±1%) corresponding to standard drying quality. The reported difference originated by assuming the initial MC of the board as equal to that of the piece of wood (slice) taken from the board. However, by assuming the initial MC of the slice, the drying tests produced an average of 8.9% final MC of the slices, i.e. slightly higher than the targeted 8% final MC.

In terms of other quality features such as deformations (deformations, bow, crook and twist), all ntholo boards experienced fair means and deviations despite being assessed on 1 m length boards. Therefore, small differences in the magnitude of deformations are expected when longer boards are dried.

Particularly, the recorded ntholo cup is likely to be connected to ntholo´s low coefficient of anisotropy.

3.5 Relationships between wood anatomical features, density and mechanical properties of ntholo

This part of the study included determination of ntholo density and mechanical properties for comparison with other well known Mozambican timbers as a way to evaluate prospective end-uses (Table 5).

Table 5. Comparison of ntholo mechanical properties with other species.

	Wood species			
Wood properties	Ntholo	Umbila[a]	Chanfuta[a]	Jambire[a]
MOE (N/mm^2)	17263	8200	13100	13600
MOR (N/mm^2)	119.2	82	108	112
Impact bending(kJ/mm^2)	81.46	57.1	79.2	69
Hardness parallel to grain	7.21[b]	5500★	8229★	7251★
Compression parallel to grain (N/mm^2)	55.68	50.00	-	69
Density 12% MC (kg/m^3)	1024	590	670	990

Sources: a – (Takawira-Nyenya 2005; Lemmens 2008; USDA Forest Service)
b – Brinell hardness; ★ Janka hardness.

The comparisons drawn between ntholo properties and the three principal commercial timbers (umbila, chanfuta and jambire) reveal clearly that ntholo is a heavier wood species with superior mechanical properties. Jambire is the closest in terms of density. In Mozambique, the main traded timbers are generally used for furniture, window frames, flooring and doors. Ntholo density is likely to be undesirable feature for mobile furniture such as chairs, tables and benches. However, ntholo hardness seems suitable for flooring.

3.5.1 Correlations between wood anatomical features, density and mechanical properties

Paper IV provides a full correlation matrix table involving all described anatomical features with corresponding density and mechanical properties. Table 6 below is a simplified matrix listing mostly significant correlation coefficients.

Table 6. Selected correlation coefficients between anatomical features, density and mechanical properties.

	Sapwood		Heartwood	
Anatomical features	MOR	MOE	Compression // grain	Hardness perp. grain
% Fibres	0.527*	0.314	-0.029	-0.198
% Parenchyma tissue	-0.549*	-0.288	0.043	0.273
Fibre length	0.471*	0.697*	-0.61*	-0.449*
Fibre wall thickness	-0.284	-0.488*	-0.447*	-0.103
Density at 12% MC	0.463*	0.486*	0.201	0.561*

* Significant correlation coefficients at p = 0.05

Ntholo sapwood samples produced the majority of significant correlation coefficients than heartwood samples. Table 6 shows that fibre length is proportional to static bending strength of sapwood samples, but inversely proportional to heartwood hardness and compression strength. In terms of ground tissue composition, sapwood MOR is associated with fibre proportions, but negatively correlated to proportion of parenchyma tissue. These interrelationships are connected to the reported specialized roles of the mentioned tissues in the tree xylem (Bowyer et al. 2003; Barnett & Jeronimidis 2003). The thickness of the fibre walls are significantly and negatively correlated to the sapwood MOE and compressive stresses applied along the grain of heartwood samples. In fact, thicker fibre walls are likely to be less elastic and might show tendency to be brittle. Like in other hardwoods, ntholo density is also proportional to some mechanical properties such as sapwood static bending strength and heartwood hardness.

3.5.2 Predicting density and mechanical properties from wood anatomical features through Partial least square and simple linear regressions

This section of the study was aimed to predict density and mechanical properties from a set of anatomical features. Separately, density was used to predict mechanical properties. This was achieved through regression analysis, namely partial least squares (PLS) and simple linear regression. In addition, PLS was carried out to identify key anatomical predictors. The regression equations generated from PLS are summarized in Table 5 of Paper IV. Despite a single significant regression equation (MOE), the results show that all sapwood mechanical properties are governed by ground tissue proportions. All heartwood regression equations are not significant. Under PLS, density is negatively affected by % of vessel proportion and positively influenced by the thickness of the fibre walls. Indeed, despite containing extractives, ntholo heartwood vessel proportion represent empty spaces in the xylem, while thicker fibre walls provide more cell wall material with reduced cell lumina.

3.5.3 Prediction of mechanical properties from wood density

Several studies have tested the predictability of mechanical properties from density on various wood species. Different results were reported (Betka et al 2002; Zhang 1997). The density of some wood species was reported as good predictor, while the density of other timber species was poor estimators. The Table 7 summarizes the performance of ntholo density as a single predictor of some mechanical properties through simple linear regression.

Table 7. Simple linear equations to predict mechanical properties from density.

	Simple Linear Regression Equations					
Mechanical Properties	**Sapwood**	R^2 adj (%)	p	**Heartwood**	R^2 adj (%)	p
MOE	$17.1\mathbf{D}_{12} - 2679$	19.4	0.03	$0.187\mathbf{D}_{12} - 72.7$	23.2	0.016
MOR	$0.196\mathbf{D}_{12} - 47.7$	17.1	0.04	$38880 - 21.1\mathbf{D}_{12}$	1.6	0.263
Compr. parallel	$57.8 - 0.04\mathbf{D}_{12}$	0.0	0.61	$0.0646\mathbf{D}_{12} - 36.6$	0.0	0.382
Compr. perp	$115 - 0.142\mathbf{D}_{12}$	45.8	0.001	$0.0821\mathbf{D}_{12} - 70.9$	4.1	0.189
BH parallel	$0.005\mathbf{D}_{12} + 1.57$	0.0	0.338	$0.00762\mathbf{D}_{12} - 0.59$	4.7	0.175
BH perp	$3.36 - 0.00063\mathbf{D}_{12}$	0.0	0.67	$0.0066\mathbf{D}_{12} - 2.44$	27.9	0.008

$\mathbf{D}_{12}$ – density at 12% moisture content; $\mathbf{R^2}$ **adj (%)** –adjusted coefficient of determination; BH-Brinnel hardness.

In general, the results show that ntholo density is a poor estimator of the tested mechanical properties. The largest observed R^2 was for sapwood hardness parallel to grain and yet the density explains less than 50% of the hardness variance. The predictability of mechanical properties from density is even weaker for heartwood samples since the maximum observed R^2 values describe less than 30% the variance of ntholo mechanical properties. Therefore, the results suggest that ntholo belongs to the group of hardwoods species in which the density alone is a poor predictor of mechanical properties such as *Populus cathayana, Populus tomentosa* and *Castanopsis fargesii* (Zhang 1997).

4. CONCLUSIONS

The present study represents an early attempt to promote lesser known/used wood species from Mozambique through comprehensive studies on selected wood properties. The study comprised an extensive review on presently used and traded wood species with a view to expand the resource base through inclusion of lesser known wood species. The review set baseline for further studies and concluded that the currently traded Mozambican wood species are generally very hard, dense, with high mechanical strength and natural durability. In addition, the timber sector survey also concluded that in Mozambique some lesser known wood species such as metonha *(Sterculia quinqueloba)* showed comparable properties in relation to the well known timber species chanfuta *(Afzelia quanzensis)*. However, the use of metonha is still very limited due partly to poor or lack of knowledge on its properties and scrutinised end-use assessment. The review concludes that further research to determine the properties and suitable end-uses of other lesser known species is of urgent need as it may help to boost the country timber sector on a sustainable basis.

Following the baselines from the timber sector review and based on the recent forest inventory, three abundant lesser known wood species were selected and sampled to describe respective wood anatomy and tentatively preview and discuss their properties. The wood anatomical study concluded that both muanga and ntholo share similar structures likely to be suitable for applications demanding strength. Furthermore, the abundance of extractives clogging heartwood vessels of muanga and ntholo typifies species with good natural durability. The study also concluded that unlike muanga and ntholo, metil is a much lighter wood probably caused by high proportion of thin-walled axial parenchyma in comparison with other major tissues. Metil structure also showed features like wide vessels lacking extractives observed in much lower density. Another concluding remark suggests that metil anatomical features are similar to timbers with poor natural durability, although this problem can be amended by impregnation with wood preservatives to which metil have shown good prospects in terms of uptake.

The third section of the study is concerned with drying experiments of ntholo which consisted of NSD tests and laboratory batch kiln drying. The experiments with ntholo drying concluded that NSD tests allowed the selection of a successfully provisional drying schedule (T6-D2). The study assessed quality features of the dried boards under T6-D2 in laboratory batch kiln drying and concluded that a standard quality was ensured after minor adjustments on the selected schedule. Another observation from the study suggests that some modification of this schedule may be a recommendable option if longer boards are to be dried. In terms of end-uses, ntholo timber seems suitable for floorings, doors and window frames. However, the use of ntholo as construction timber does not appear appropriate considering its high density.

The final part of the study explored the relationships between anatomical features, density and mechanical properties of ntholo. The objective was to present mechanical properties of ntholo and compare with well known timbers with view to assess and possibly propose end-uses. The study also examined interrelationships through correlation analysis, prediction of density and mechanical properties from a set of anatomical features through regression analysis. For practical reasons, ntholo density was used to predict mechanical properties. The study concluded that ntholo is a very dense timber with high mechanical strength and instead of being used as an alternative to the well known timbers, ntholo is proposed to be grouped in the short list of available heavy timbers in Mozambique.

The interrelationships through correlation analysis concluded that fibre length is the only anatomical feature significantly correlated to density and all tested mechanical properties of ntholo. The same was observed between density and mechanical properties. On the contrary, both 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 PLS.

MOE of sapwood was the only significant regression equation on mechanical properties. In addition, the study concluded that all tested properties of ntholo sapwood are greatly influenced by tissue proportions. In general, ntholo heartwood properties were described by more leveled anatomical predictors. Invariably, the fibre dimensions and vessel features seemed to be the key variables. Based on regression analysis, it was concluded that both sapwood and heartwood densities are weak predictors for the tested mechanical properties. However, due to some of the observed significant correlations between density and tested properties, the use of density can still provide rough indication for selection of ntholo raw material for designated end-use applications.

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