Chemical Composition and Machinability of Selected Wood Species from Mozambique

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Abstract

The objectives of the current work were to carry out a survey on timber sector in Mozambique and to determine chemical, calorific and machinability features of selected species. Mozambican timber sector was described as dominated by selective harvesting practices on a few hardwood species out of 118 species growing in the forest with potential for industrial timber. Selective logging is believed to be due to the demand in both domestic and international markets of traditionally used, and lack of technical data on lesser used species. In order to avert the negative effect of selective logging, this work argued the need to widen the resource base by studying lesser used species. Taking into account stock volumes recorded in the last forest inventory, the lesser used species, *Acacia nigrescens* Oliv, *Icuria dunensis* Wieringa, *Pseudolachnostylis maprounaefolia* Pax, and *Sterculia appendiculata* K. Schum were selected to assess their chemical, calorific and machinability features. Lesser used species were compared with traditionally used species, namely, *Afzelia quanzensis* Welwn, *Milletia stuhlmannii* Taub, *Pericopsis angolensis* Meeweven, and *Pterocarpus angolensis* DC, regarding chemical and calorific features. Aiming to get a thorough chemical characterization along radial direction, samples for chemical analyses were taken from the sapwood, and outer and inner heartwood. Chemical and ultimate analyses were performed according to standard methods. The contents of carbohydrates, extractive, ash, volatiles and high heating values were in ranges considered normal for tropical species. Contents of lignin and minerals were unexpectedly high in *Pseudolachnostylis,* reaching 37.51 % and 2.2 % (wt%, extractive free) on a dry weight basis, respectively. Based on the determined chemical features, it was concluded that *Acacia* and *Pseudolachnostylis* were similar to well-known, whereas *Icuria* and *Sterculia* differed from the known species. In ranking of all studied species using fuel wood value index (FVI), *Acacia* was best ranked, whereas *Sterculia* was worst ranked. *Acacia, Pericopsis, Pseudolachnostylis* and *Sterculia,* considered as lesser used in the study, were subjected to experiments for cutting forces and tool wearing measurements. Density measurements on samples for cutting forces and tool wearing experiments were performed with the aid of a CT scanner. Two different cutting tools 20° and 30° rake angle were used. Before cutting, the edge radius of the tools was measured. Main cutting force in 90°-90° and 90°-0° cutting directions were measured by piezoelectric gauge. Tool wearing experiments were performed on a shaper using cemented carbide tools for woodworking and fixed cutting conditions. Edge recession and tool wear radius were measured for monitoring tool wearing. Ranking the species using cutting forces only or tool wearing only for machinability recorded different earnings, and for measuring the net effect of machining output variables, this work suggested the Digraph and Matrix Method as an expeditious and integrated method to evaluate the machinability of lesser used species. Based on the calculated indexes, the easiest species to be machined was *Sterculia*, whereas the most difficult species to be machined was *Acacia*. Cutting forces earned by *Acacia* seemed to have been affected by anatomical features not measured in the current work.

Keywords: chemical composition, cutting forces, fuel wood, lesser used species machinability, Mozambique, tool wear, tropical hardwood species

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Dedication

To the memory of my parents

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., Uetimane Jr, E., Lhate, I., Terziev, N. (2008). Anatomical characteristics, properties and use of traditionally used and lesser known wood species from Mozambique: a literature review. *Wood Sci Tecnhol*, 42, 453-472.

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

III Cuvilas, C., Lhate, I., Jirjis, R., Terziev, N. (2011). Characterization of wood species from Mozambique as fuel. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* (*In Press*).

IV Cristovão L., Lhate, I., Grönlund, A., Ekevad, M., Sitoe, R. (2010). Tool wear for lesser known tropical wood species. *Wood Material Science and Engineering*. DOI: 10. 1080/17480272. 2011. 566355.

V Lhate, I., Cristovão, L., Ekevad, M., Sitoe, R. (2010). Cutting forces for lesser used species from Mozambique. Accepted for Wood Machining Conference to be held in Skellefteå in June, 7-10, 2011.

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The contribution of Inácio Lhate to the papers included in this thesis was as follows:

I	Inácio Lhate (30 %)
II	Inácio Lhate (80 %)
III	Inácio Lhate (40 %)
IV	Inácio Lhate (40 %)
V	Inácio Lhate (70 %)

Abbreviations

CT	Computer Tomography
DNFFB	Direcção Nacional de Florestas e Fauna Bravia (National Directorate of Forest and Wild Life)
EMC	Equilibrium moisture content
ER	Edge recession
FVI	Fuel wood Value Index
HHV	High Heating Value
LU	Lesser used
MC	Moisture content
TW	Tool wear radius

1 Introduction

Depending on genetic features, trees are sources of renewable material for several purposes including furniture, construction, fuel wood, etc. The use of renewable materials is becoming increasingly necessary for achieving the changes required to address the impacts of global warming.

Biomass is the plant material derived from the reaction between CO_2 in the air, water and sunlight, via photosynthesis, to produce carbohydrates that form the building blocks of biomass. The solar energy driving photosynthesis is stored in the chemical bonds of structural components of biomass. If biomass is processed efficiently, either chemically or biologically, by extracting the energy stored in the chemical bonds and the subsequent "energy" product combined with oxygen, the carbon is oxidized to produce CO_2 and water. The process is cyclic as the CO_2 is then available to produce new biomass. Burning fossil fuels uses "old" biomass and convert it into "new" CO_2, which contributes to the "greenhouse" effect and depletes a non-renewable ressource. Burning new biomass contributes no new carbon dioxide to the atmosphere, because replanting harvested biomass ensures that CO_2 is absorbed and returned for the cycle of new growth (McKendry 2002).

Mozambique forests guidelines lists 118 wood species of industrial importance grown in forests, and yet a few of them provide the bulk of all material available for domestic and international commercial use. The others species are seldom used because their properties and end uses are poorly known. Timber of many species is still exported in form of logs because the species are difficult to machine or to season. Mozambique timber species are known to exhibit large diameters, attractive texture, high mechanical strength and natural durability and are mainly used for furniture, timber, plywood and outdoor applications.

The current logging system has been the eroding ecological balance of forests in Mozambique. Selective logging is believed to be due to the demand in both domestic and international markets for traditionally used species, and lack of technical data on lesser used species. Figure 1 shows in proportion the harvested timber per species in 2004. According to Annual Statistical Report of 2004, chanfuta, jambire and umbila together accounted for 79 % of the total timber production of the country, although there are many other wood species in the "miombo" biodiversity rich forests.

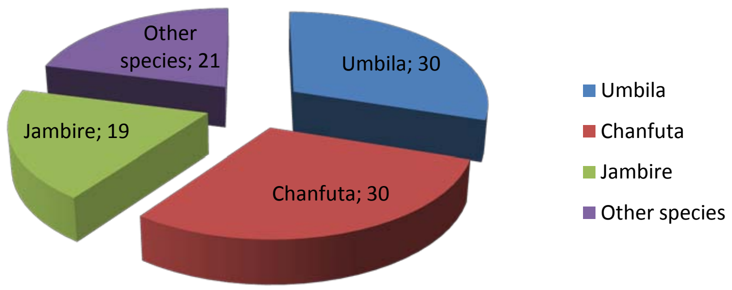

Figure 1. Proportion of exploitated species – Source : DNFFB (2005)

In order to avert the negative effect of selective logging, this work suggested the need to widen the resource base by studying lesser used species. Taking into account stock volumes recorded in the last forest inventory, five lesser used species, namely, *Acacia nigrescens* Oliv, *Icuria dunensis* Wieringa, *Pseudolachnostylis maprounaefolia* Pax, and *Sterculia appendiculata* K. Schum were selected to assess their chemical, calorific and machinability features. Another aim was to compare these species with traditionally used species, e.g. *Afzelia quanzensis* Welwn, *Milletia stuhlmannii* Taub, *Pericopsis angolensis* Meeweven, and *Pterocarpus angolensis* DC, regarding chemical and calorific features.

Geometry and size of logs from Mozambique forests make it difficult to include chipper canters and circular saws in sawing sheds, unless logs are especially selected to fit sawing with circular saws. Band saws are mainly used to perform through and through sawing. Debarking is not used as preparatory processing for sawmilling. Slabs are used by local people as fire wood or construction material.

1.1 Sawmilling by–products handling in Mozambique timber sector

Mozambique forestry industry does not manufacture pulp and board products. Large amount of logging and sawmilling residues are burnt or disposed of. Logging residues are disposed of or burnt at local communities to prevent loopholes related to saw-log size. Logs below allowable diameter are presented at check points as branches.

Despite increasing demand for wood, and serious reduction of the forest resource base in Mozambique, sawmilling has been reported to be wasteful. The logs are not debarked prior to sawmilling, the slabs are not used to manufucture items of less aesthetic values (e.g., hidden parts of drawers) and the sawdust is often disposed of in Mozambique.

1.2 Description of trees and habitat of lesser used species from Mozambique

The review on timber sector highlighted a remarkable decline of well known species in Mozambique forests. Taking into account the last forest inventory, five lesser used (LU) species were selected in order to widen the resource base of the country.

1. *Acacia nigrescens* is a deciduous 25-30 m high tree. Its habitat is primarily wooded grassland, particularly on alluvial soils by rivers and lakes. It occurs from Tanzania southward to north-eastern Namibia, Botswana and north-eastern South Africa (Lemmens 2006).
2. *Icuria Dunensis* is endemic to Mozambique in Nampula and Zambezia provinces. The species is found mainly in Moma district coastal dunes in evergreen forests as isolated patches composed of trees that can reach heights up to 40 m (Coastal and Environmental Services 2001). Wieringa (1999) reported that the trees occur in large communities.
3. *Pseudolachnostylis maprounaefolia* is characterized by small trees, 5-10 m high and trunk around 30 cm in diameter. *Maprounaefolia* grows by rivers, especially in plateau areas of open forest on sandy clay with frequently yellow soils (Global Diversity information Facility, n.d.; Marzoli 2007).

4. *Pericopsis angolensis* is a deciduous small to medium-sized tree up to 20-27 m high with a branchless bole up to 7.5 m. *Pericopsis angolensis* is locally common in deciduous, open or closed woodland and wooded grassland up to 1650 m altitude. It is often found in miombo woodland in association with *Brachystegia*, *Combretum* and *Terminalia* species. It has been reported that this species occurs from eastern DR Congo and Rwanda east to Tanzania, and south to Zambia, Angola, Zimbabwe and Mozambique (Lumbile & Oagile 2008).
5. *Sterculia appendiculata* is a tall deciduous tree, growing up to 40 m, often with a long, unbranched trunk. This species is mainly found in Malawi, Mozambique, Tanzania and Zimbabwe (Flora of Zimbabwe n.d.).

As a follow-up, the selected LU species were subjected to experiments with the aim to gather their main properties and facilitate industrial use (Uetimane Jr *et al.* 2009; Ali *et al.* 2010; Uetimane Jr *et al.* 2010). Current work dealt with characterization of chemical and calorific features of well-known and LU species. In addition to chemical characterization, machinability features of *Acacia, Pseudolachnostylis, Pericopsis* and *Sterculia* were studied. *Icuria* was included only in chemical experiments because it is an endangered species, used only by local communities as fire wood or for construction purposes, and thus it was not included in the study of machinability.

1.3 Chemical and calorific value experiments

The chemical composition varies within a tree part (root, stem and branch). There are two major components of wood: lignin and carbohydrates. Both are complex polymeric materials. Minor amounts of extraneous materials, mostly in the form of extractives and inorganic minerals (ash) are also present in wood. Elemental composition of wood comprises carbon, hydrogen, oxygen and trace amounts of metal ions. Klason lignin is considered the least expensive procedure in terms of quantification and instrumentation and is the easiest to handle among the procedures of lignin determination. Carbohydrate content in wood is usually determined by gas liquid chromatography, whereas extractives are determined by Soxhlet method when using several types of solvents. Metal ions are usually determined by various methods of spectrometry.

Chemical composition of wood has an influence on the physical and mechanical properties. In the cell wall for example, low molecular weight substances occupy the same space in which hygroscopic water could enter. Due to this, extractives lower the EMC of wood and reduce swelling and shrinking (Killic & Niemz 2010; Singleton *et al.* 2003). Moreover, knowledge on the chemical composition of wood is important for assessment of natural durability and calorific value (Santana & Okino 2007; Duku *et al.* 2010). Ash analysis is performed to assess concentrations of minerals influencing both combustion and machinability performances. Silica and calcium carbonate deposits can influence profoundly machinability of tropical wood species (Loehnertz *et al.* 1994). Extractives can play a dual role during wood machining, they can either facilitate by lowering the friction coefficient between the woodkpiece and the tool (Svesson *et al.* 2009) or aggravate by removing the binding element in cemented carbides of the tool (Klamecki 1979; Svesson *et al.* 2009). According to Bowyer *et al.* (2003), a high content of lignin and extractives raises the heating value and affects the wood density. The concentrations of nitrogen (N), sulphur (S) and chlorine (Cl) in different biofuels are also of major importance because they can upon combustion, be emitted as NO_x, SO_2 and HCl. The formation of these gases also depends on other parameters such as excess oxygen, CO concentration in the flue gas, furnace temperature and geometry (van Loo & Koppejan 2003). Nitrogen is almost completely converted to the gaseous phase (N_2, NO_x) during combustion. While the Cl contained in the biofuel mainly forms gaseous HCl, Cl_2 or alkali chlorides such as KCl and NaCl, a large part of Cl released (40-80 %) condenses as salts and is integrated in ash. The sulphur (S) contained in the solid biofuel forms mainly gaseous SO_2 (and to a certain extend SO_3) and alkali as well as earth-alkali sulphates. Forty to seventy percent of sulphur contained in the fuel is integrated in ash (Obernberger *et al.* 1997).

Depending on the magnitude of the ash content, the available energy of the fuel is reduced proportionally. In combustion processes, ash can react to form a "slag", a liquid phase formed at elevated temperatures, that can reduce plant throughput and result in increased operation costs. Moreover, the reaction of alki metals with silica present in the ash produces a sticky, mobile liquid phase, which can lead to blockage of air ways in the furnace and boiler plant (McKenndry 2002).

The whole process of wood utilization as source of energy (fuel recovery and combustion) and the type of gaseous emissions is influenced by the physical and chemical characteristics of the wood fuel (van Loo & Koppejan 2003). Information concerning these parameters is valuable for the evaluation of indigenous wood species available as a fuel. It is also needed by the wood fuel producer sector, since fuel quality can be influenced by the handling of the biomass during recovery processes (Obernberger 1997).

1.4 Cutting forces in wood machining

Basic aspects of wood machining such as chip formation, surface quality, and tool life can be better understood with knowledge of the cutting forces needed during orthogonal cutting (Wodson 1979).

Cutting forces have been considered as the main output parameter for physical description of the cutting process. Other possibilities, such as vibration, sound, temperature, cutting power, deformation, surface quality and chip quality measurements, have been normally neglected. The main reason is that measurement of cutting force is a powerful tool allowing building of physico-mechanical cutting models for better understanding of the phenomena observed during cutting.

Some cutting force models have been elaborated to understand the mechanical behaviour of the wood materials tested and others models to characterise the machinability of various wood materials (Marchal *et al.* 2009). A model that controls cutting forces for estimating wood behaviour and surface quality, tool capability, and optimising cutting conditions has been elaborated by Eyma *et al.* (2004). A study focusing particularly on the influence of physical and mechanical characteristics of wood during secondary processing and another study for comparing cutting forces obtained with a routing machine and those obtained with a pendulum have been reported by Eyma *et al.* (2002, 2005). Models for estimation of the effect of tool wear on cutting forces can also be found in literature (Aknouche *et al.* 2009).

1.5 Tool wear in wood machining

The wear of the tool is connected to negative aspects of the production process, namely, downtime for tool change, increased cutting forces and roughness of surfaces.

In the wood working industry, tool wear is particularly connected with high contents of silica and calcium if machining tropical wood species (Loehnertz *et al.* 1994; Torreli & Cuffar 1995). In the current work, tool wear was evaluated by edge recession and tool wear radius measurements.

1.6 Machinability

One of the reasons for under performance of the Mozambique forestry sector is the exportation of timber in round form. Mozambique has several very dense hardwood species that are difficult to saw domestically, but are sold and sought after for export on the international market for manufacture of traditional dark, ornate furniture (Ogle & Nhantumbo 2006).

Machinability is influenced by a number of variables, including properties of the workpiece materials, cutting material, tool geometry, nature of tool engagement with cutting fluid and machine tool rigidity and capacity. These variables are machining process input variables and are independent of the machining process. On the other hand, the machining process output is marked by dependent process variables, such as tool life (or tool wear), cutting forces, power consumption, dimensional accuracy, etc. The dependent process variables are the function of process input variables and refer to the performance of work material during machining operation in terms of technical and economic consequences, and are directly related to machining operations, and hence to machinability. Thus, these are considered as pertinent variables to represent the machinability of a given work material for a given operation (Rao 2005).

The study of cutting forces and tool wear was aimed to assess primary and secondary processing characteristics of LU species. Tertiary processing characteristics (e.g. wood drying of ntholo) were assessed previously by Uetimane Jr *et al.* (2010).

Both the cutting forces and tool wear can each be used for evaluating the machinability of workpiece material. Low density and high mineral content species will earn low cutting forces, but high tool wear and vice versa. An integrated parameter that combines cutting forces, tool wear and other parameters will offer a better description.

1.7 Limitations of the study

A number of factors, such as transportation of samples from sampling sites to final destination, characteristics of sampling sites (natural forests), negligible amount of sapwood in logs (particularly in *Pericopsis)* and absence of boundary between sapwood and heartwood in *Sterculia* wood species imposed several difficulties in the current research work.

Sampling sites were characterised by different rainfall (Paper II), different soil fertility and microclimate. All the afore mentioned sampling site characteristics are sources of variability within and between species and between sampling sites within the same species (Baker *et al.* 2003; Gryc &

Horácek 2007). An effort was made to comply with the standard Copant (1972)with sampling of five trees in each stand.

The present research work was carried out at the Swedish University of Agricultural Sciences and Luleå University of Technology. The samples for the experiments were collected in Mozambique. The samples were transported by express air transportation to prevent biodegradation and moisture loss. The arrangements for transportation limited the amount of material that could be collected and brought to Sweden, and therefore, determined the sample size for statistical analysis.

Extractives are present in greater amounts in the heartwood than in the sapwood and the changes in content can be very abrupt at the heartwood periphery (Hillis 1968; Hillis 1971; Dünisch *et al.* 2010). A number of these extractives are often biocidal and could also be largely responsible for the colour of the wood (Antwi-Boasiako *et al.* 2010). All species studied in the current work showed a marked boundary between sapwood and heartwood (probably due to extractives) except for Sterculia.

In tropical forests the age of trees is usually unknown and in the present work, this was not an exception. Thus, some variation in age between trees and species was inevitable. The approach of counting annual growth rings is limited to trees of which accurate information about the date of planting is available, i.e. the case for trees from plantations, botanical gardens, etc. (Verheyden *et al.*2004; Worbes 1995).

Negligible amounts of sapwood in *Pericopsis* and absence of boundary between sapwood and heartwood in *Sterculia* made it difficult to perform cutting force experiments and tool wear for sapwood.

1.8 Objectives of the study

This work aimed to provide chemical composition, calorific features and machinability of selected species from Mozambique. Special attention is paid to LU species regarding comprehensive description of their chemical composition, fuel wood values and machinability characteristics. The description of LU species is intended to stimulate their commercial use in order to reduce the selective logging currently characterising the timber sector in Mozambique.

The main objectives of the study were:

1. Carry out a survey on the timber sector in Mozambique and find tentative solutions to the problems created by selective logging;
2. Assess chemical and calorific features of lesser used species from Mozambique;

3. Build a model based on an integrated parameter for assessment of the machinability of lesser used wood species.

2 Materials and Methods

Revision of the timber sector data in Mozambique was relevant for obtaining a better insight, and trying to address the negative impact of selective logging particularly through the enlargement of the resource base. In addition to the survey on the timber sector, the study included experiments for chemical composition, calorific value and machinability features of the selected species.

2.1 Sites and sampling

The studied hardwood species are listed in Table 1. Field sampling for *Acacia, Afzelia, Icuria*, *Milletia*, *Pericopsis, Pseudolachnostylis, Pterocarpus*, and *Sterculia* was carried out according to COPANT (1972).

Table 1. *Tropical hardwood species from Mozambique*

Scientific name	Vernacular name	Family
Acacia nigrescens[a]	Namuno	*Leguminosae*
Afzelia quanzensis	Chanfuta	*Fabaceae-Caesalpinioideae*
Icuria dunensis[a]	Icuria	*Fabaceae*
Milletia stuhlmannii	Jambire	*Fabaceae-Faboideae*
Pericopsis angolensis[b]	Muanga	*Fabaceae-Faboideae*
Pterocarpus angolensis	Umbila	*Fabaceae-Faboideae*
Pseudolachnostylis maprounaefolia[a]	Ntholo	*Bopyroidea*
Sterculia appendiculata[a]	Metil	*Sterculiaceae*

[a]LU species

[b] Emerging species

Five trees of each species were obtained from open dry forest subjected to frequent fires set by local people as a result of shift cultivation and traditional hunting routines in each sampling stand.

The stands were chosen in the northern and central parts of Mozambique, namely, in the provinces of Cabo Delgado (north), Nampula (north) and Sofala (centre). The locations of the three provinces are given in Table 2 (Wikimedia Commons 2008). Annual rainfall of the provenances is shown by data from Ribeiro (2002) and Wulff and Torp (2005).

Table 2. *Provenances, geographical coordinate annual rainfall and collected species*

Provenance	Latitude	Longitude	Annual Rainfall mm	Collected Species
Cabo Delgado	12°45'0" S	39° 30' 0" E	1400-1800	Chanfuta, Jambire, Metil, Muanga, Namuno, Ntholo, Umbila
Nampula	15° 15'0" S	39° 30' 0" E	1400-1800	Chanfuta, Icuria, Jambire, Umbila
Sofala	19° 0' 0" S	34° 45'0" E	1000-1200	Chanfuta, Jambire, Umbila

The selection of the stands aimed at covering variation within northern and central regions of Mozambique collectively and not to study provenance effect on studied features. Each stem of the considered species was cut to three logs of 1.2-m length depicted as bottom, middle and top log.

2.2 Sample preparation and laboratory analysis

The samples had to be prepared in agreement with the corresponding standards or in suitable sizes for the clamping device on the equipment. Samples for chemical analysis were similar to those for calorific value whereas the difference between samples for cutting forces and tool wear resided mainly in size.

2.2.1 Laboratory analysis for chemical and calorific value characterization

Butt logs were through-and-through sawn to 50-mm-thick planks that were wrapped and stored at -20 °C.

Preparation of samples included oven drying before grinding of samples for chemical and calorific value analyses, and climate conditioning to attain 12 % MC for density measurements. Afterwards, several standard experiments were carried out for determination of pertinent parameters according Table 3.

Samples were taken from the butt logs at breast height (1.3 m) for all species. The samples (3-5 cm thick discs) for chemical analyses were taken along the radius, namely sapwood, outer heartwood, and inner heartwood for all species except metil. The boundary between sapwood and heartwood in metil is invisible; therefore, the whole length, excluding juvenile wood was used. For calorific value characterization the samples were taken identically as for metil. The samples were dried at 105°C to constant weight, debarked, chipped and ground to pass 1.0 mm mesh. The samples were analyzed for monosaccharides, lignin, extractives, ash content, heating value and minerals in ash. In addition, the same samples were used for ultimate analysis. Klason lignin was presented as ash free.

By-products of hydrolysis, such as acetic acid, 4-O-methylglucuronic acid, HMF (5-hydroxymethyl-2-furfuraldehyde), furfural, soluble lignin and levulinic acid were not considered in this study.

Analyses of minerals content were carried out on LU and well known species that showed high ash content.

Ranking of the studied species as fuel wood was performed using the fuel wood value index (FVI) which is often used to characterise the overall quality of the fuel by accounting for several important parameters, such as higher heating value, density, ash content and MC (Labrecque *et al.* 1997; Deka *et al.* 2007; Goel & Behl 1995; Chettri & Sharma 2007). The FVI was calculated using the following formula:

$$FVI = \frac{HHV(kJ/g) x Density(g/cm^3)}{Ash(g/g)} \tag{1}$$

The moisture content (MC), which can vary among different species, and negatively influences the energy obtained from the fuel wood was not included in the formula due to logistic difficulties during samples collection.

Table 3. *Parameters analysed, methods and standards*

Parameter	Method	Standard
Monosaccharides	Hydrolysis/Gas-liquid chromatography	T 249 cm-00
Ash content	Gravimetric	SS187171:1
Extractives	Gravimetric /Soxhlet extraction (acetone)	SCAN-CM 49 :03
Lignin	Gravimetric /Klason lignin	T 222 om-06
Sb, B, Al, As, Cd, Co, Cu, Cr, Mo, Ni, V, Sn, Zn, Se,Ti	Inductively Coupled Plasma/Mass Spectrometry (ICP-MS)	NMKL161
Hg	Atomic Fluorescence Spectrometry (AFS)	NMKL170
Ca, Fe, K, Mg, Mn, Na, Ba, Cd, Ti	Inductively Coupled Plasma / Atomic Emission Spectrometry (ICP-AES)	NMKL161
Pb	Inductively Coupled Plasma/Mass Spectrometry (ICP-MS)	ALC208:902
Si	Atomic absorption spectrometry (AAS (Flame))	ALC208:201
Density	Mass/displacement	ISO 3131
High heating value	Combustion in a calorimeter bomb (Parr 6300)	SS 187182
C, H, N	Combustion at 1050˚C (LECO CHN 1000)	
O	Calculated as difference between 100 and the sum of C and H	
S	Furnace combustion in oxygen at 1350˚C with infrared detection procedure	SS18177:1
Cl	Using Eschka mixture, titration by Mohr procedure	SS 187154:1
Volatiles	Heating at 900˚C without contact with air during 7 minutes	SS - ISO 562:1

2.2.2 Experiments for machinability features

Density, cutting forces and tool wear measurements were preceded by preparation of samples sized 120 × 200 × 1000 mm along the grain, for tool wear and 80 × 80 × 1200 mm, for cutting forces, in radial, tangential and longitudinal, directions, respectively. All samples were taken from the heartwood region excluding juvenile wood. The samples were dried in room climate to 8-9 % MC. Afterwards, samples for cutting forces were cut to 70 × 70 × 160 mm.

Wood density measurements were carried out by a computer tomography scanner (CT-scanner-Figure 2) as by Lindgren *et al.* (1992). Slices possessed a tickness of 10 mm each and were aligned tangentially. The depth of each kerf was adjusted to cover the thickness of a slice in order to allow replication or repetition of the experiments. Tomograph images were also used to check for defects in samples. All kerfs were cut in slices free of defects.

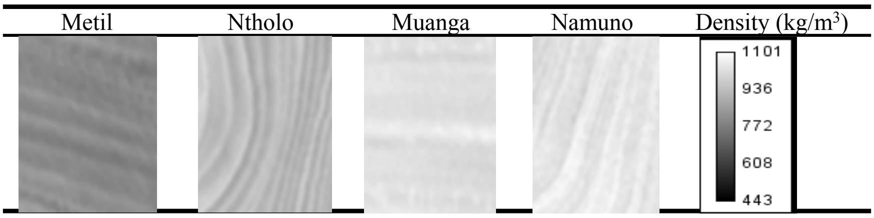

Figure 2. Grey scales CT-images showing density level of LU species from Mozambique

Cutting forces were measured on four wood species using piezoelectric sensors. Cutting forces were read 11 times per kerf (77 times per cross section). Main cutting force measurements followed the methodology of Axelsson *et al.* (1993).

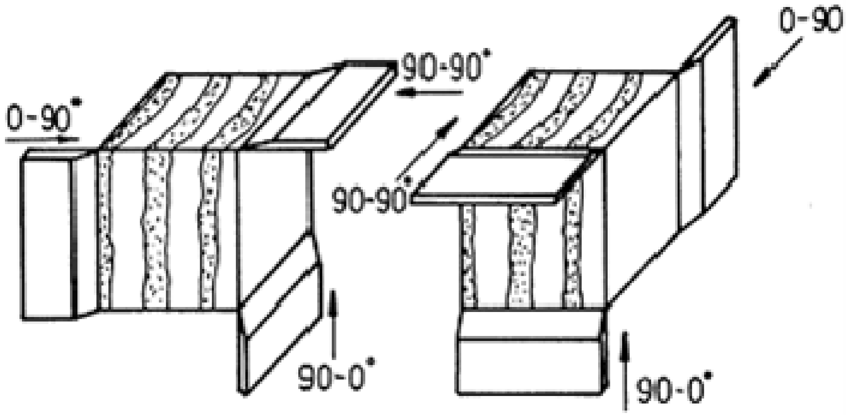

Figure 3. Cutting directions-Source: Kivimaa (1950)

Table 4. *Cutting parameters*

Designation	Value	Designation	Value
Cutting direction	90˚-90˚, 90˚-0˚	Cutting speed	15 m/s
Chip thickness	0.15 mm	Kerf width	3. 9 mm
Rake angle	20˚and 30˚	Moisture Content	6-9 %
Edge radius	25 µm	-	-

Cutting conditions for cutting force measurement were as given in Table 4. Cutting directions corresponded to rip sawing (direction 90°-90°), primary processing of wood, and planing (direction 90°-0°), secondary processing of wood.

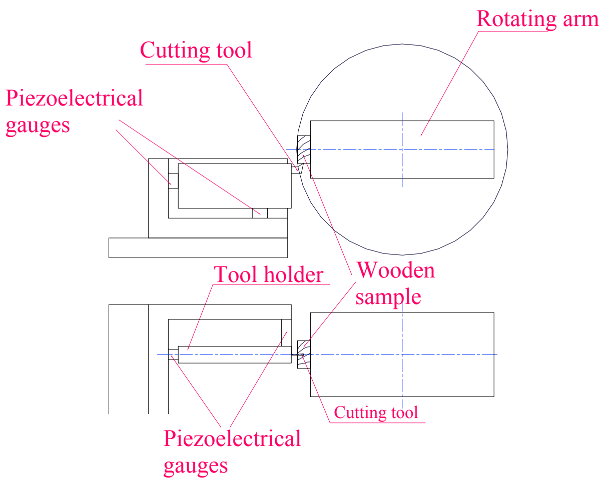

Figure 4. Schematic view of cutting forces equipment

Schematic view of the equipment for cutting force measurements is shown in Figure 4. Samples were clamped on a rotating arm and rotated (in the plane of the drawing) with it for the main cutting movement. The tool holder together with the cutting tool performed feed movement (translational motion perpendicular to the rotation of the wooden sample). Three piezoelectric gauges measured the main, feeding and side forces. The current study considered only main cutting force.

Metil, muanga, namuno and ntholo were also tested for tool wear properties. Tool wear experiments were carried out on a shaper with mechanical feed mechanism (Figure 6) under the following conditions: tool carbide grade Sandvik 701, cutterhead rotation 2900 rpm, cutterhead diameter 154 mm, feed speed 3 mm/min, cut depth 1 mm, cutting length per cut 12.41 mm, cutting width 3.9 mm, rake angle 30°, clearance angle 15°, cutting direction 90°–0° (milling parallel to grain) and a counter-mode. The workpieces were machined using a single standard saw tooth AA.

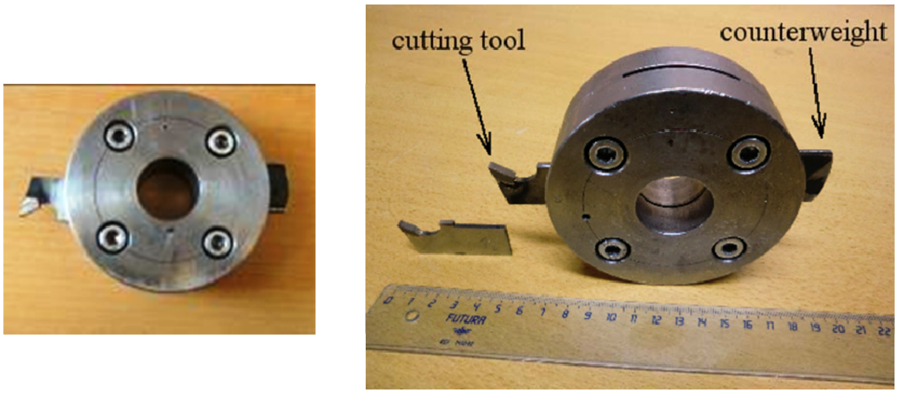

Figure 5. Cutter head with cutting tool and counter-weight

Figure 6. Shaper for tool wearing experiments

For tool wearing experiments a shaper and a special cutter head were selected (Figures 5, 6).

Cutting tool for wearing experiments was clamped in a slot located on one side of a special cutter head. In the opposite slot was clamped a counter weight to balance the counter weight in order to prevent vibration due to high rotational speed. The wooden sample performed a translational feeding motion whereas the tool performed the main rotational motion.

Tool wear was evaluated by means of two parameters to obtain a meaningful representation of tool wearing. Tool wear radius (TW) were measuredin an evaluation area in the middle position of the cutting edge with the aid of Micro–CAD (Figure 7a). An optical microscope with digital picture capturing and measurement capabilities was used for measurement of the edge recession (ER) on the rake surface (Figure 7b) at four equidistant positions in the same evaluation area as for TW. ER and TW were measured at cutting length of 4896 m.

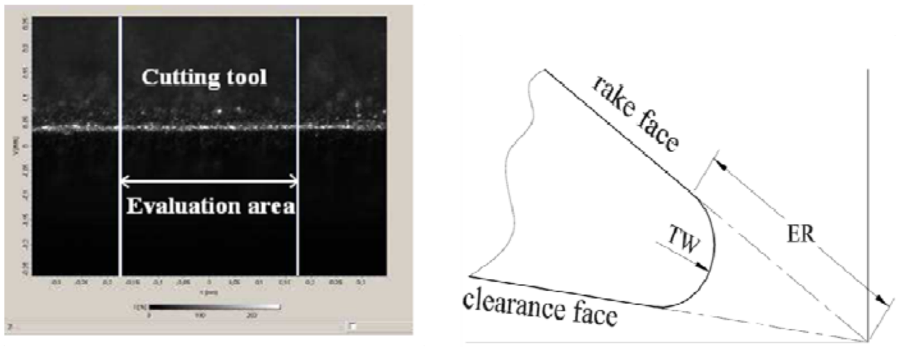

Figure 7. Tool wear radius evaluation (a), Edge recession and tool wear radius (b)

2.3 Digraph and matrix methods for machinability evaluation

In order to compare performance of the wood species when cut, a machinability index was used. The machinability index was calculated using digraph and matrix methods.

Machinability attributes considered in the current study were as given in Figure 8, tool wear (TW), cutting forces in direction 90°-0° (CF1) and cutting forces in direction 90°-90° (CF2).

$$\begin{array}{ccc} & \textit{Attributes} & \begin{matrix} TW & CF2 & CF1 \end{matrix} \\ & TW & \\ A = & CF1 & \begin{bmatrix} D_1 & a_{12} & a_{13} \\ a_{21} & D_2 & a_{23} \\ a_{31} & a_{32} & D_3 \end{bmatrix} \\ & CF2 & \end{array} \quad (2)$$

$$per(A) = \prod_{i=1}^{3} D_i + \sum_{i,j,k} (a_{ij} a_{ji}) D_k + \sum_{i,j,k} (a_{ij} a_{jk} a_{ki} + a_{ik} a_{kj} a_{ji}) =$$
$$= \textit{Machinability index} \quad (3)$$

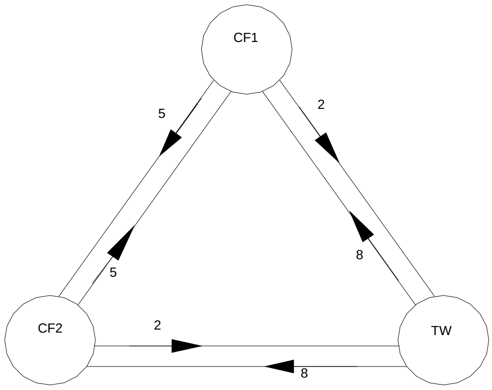

Figure 8. Machinability digraph for LU wood species from Mozambique

In the current work every attribute was considered non-beneficial to machinability. Eq. 2 gave matrix representation of machinability attributes taking into account the number of variables in present work (3 variables). Eq. 3 was the expression for machinability function considering the dimension of the matrix in Eq. 2. The permanent of matrix A, i.e. $per(A)$ is defined as universal machinability function. The permanent is a standard matrix function and is used in combinatorial mathematics (Rao & Ghandi 2002).

The values of attributes (D_i) had to be normalized in order to use the scale, from 0 to 10. For non-beneficial attributes, the attribute value 0, on the scale 0 to 10, was assigned to the worst range value (D_{iu}) and the value of 10 was assigned to the best range value (D_{il}). The other intermediate values (D_{ii}) of the machinability attribute were assigned values in between 0 and 10 as follows:

$$D_{ii} = 10\{1-(D_i / D_{iu})\} \qquad \textit{for} \quad D_{il} = 0$$
$$D_{ii} = \{10/(D_{iu} - D_{il})\} \times (D_{iu} - D_i) \qquad \textit{for}\ D_{il} > 0 \quad (4)$$

$$a_{ji} = 10 - a_{ij} \tag{5}$$

The comparison of species was also carried out by evaluating the coefficient of similarity/dissimilarity based on the numerical values of the terms of the machinability function in its grouping. The coefficient of similarity/dissimilarity lied in the range 0-1. Based on the performance, the coefficient of dissimilarity for two species was proposed as follows:

$$C_d = (1/Q) \times \sum_{i,j} \Psi_{i,j} \tag{6}$$

where

$$Q = \text{maximum of} \left[\sum_{i,j} \left| T_{i,j} \right| \ and \ \sum_{i,j} \left| T'_{i,j} \right| \right],$$

$T_{i,j}$ and $T'_{i,j}$ denoted the values of the terms for machinability function of two species under comparison and

$$\Psi_{i,j} = \left| T_{i,j} - T'_{i,j} \right|.$$

The coefficient of similarity was

$$C_s = 1 - C_d \tag{7}$$

2.4 Statistical analysis

Statistical analysis was performed to obtain an insight of descriptive statistics, grouping of species at the level of sample-position and the effect of several variables related to chemical features and cutting forces. For statistical analysis SAS software Version 9.2 was used (SAS Institute Inc. 2009).

2.4.1 Simple comparative model

Statistical analysis was performed using a simple comparative model:

$$y_{ij} = \mu_{ij} + e_{ij} = \mu + \alpha_i + e_{ij} \tag{8}$$

Where μ was the mean value for all species taken together (the so called *overall mean*), and μ_i was the mean value for species, $\boldsymbol{i}$, α_i was the difference between the mean value for species i and the overall mean, and e_{ij} is a random error (residual). In the current work α_i was considered species *effect*.

The indexes were considered in the ranges,

$$\begin{cases} i = 1,8;\ j = 1,5\ \ for\ chemical\ analysis\ (excluding\ density) \\ \qquad i = 1,4;\ j = 1,3 \qquad for\ machinability \end{cases} \quad (9)$$

The null hypothesis of the model was given by the equation,

$$\begin{cases} \mathcal{H}_0: \quad all\ \mu_i\ are\ equal\ \ in\ each\ j. \\ \mathcal{H}_0:\ All\ \alpha_i\ are\ equal\ to\ 0\ \ in\ each\ j \\ \mathcal{H}_0: \qquad \sum\alpha_i^2 = 0\ \ in\ each\ j \end{cases} \quad (10)$$

and the corresponding alternative hypothesis was that the mean values were not equal, i.e.,

$$\mathcal{H}_1 : \sum\alpha_i^2 > 0\ \ in\ each\ j \quad (11)$$

The index i stands for species in both analyses, and j for wood components (cellulose, hemicellulose and lignin) and extraneous materials (extractives and ash) in chemical analysis. In cutting forces analysis, j stands for cutting forces, density and tool wear radius.

The above described model was at level of species, the highest level of analysis. Level of tree for chemical analysis, and levels of tree and sample for cutting forces were used at an initial stage of the analysis. The variable kerf was considered auxiliary variable for model simplification.

Statistical analysis in 90˚-90˚direction (rip sawing) was made separately from 90˚-0˚ direction (planing). It is informative to note that for cutting forces experiments only heartwood was used.

Regarding the model described by Eqs. 8 and 9, it was necessary to avoid species effect when the rake angle effect was sought, i.e. the comparison had to be within the same species. In order to ensure comparison within the same species, a restriction was introduced in the model (Figure 9),

$$\begin{cases} \qquad \mathcal{Y}_{ij} = \mu + \alpha_{j+}e_{ij};\ i = 1,4;\ j = 1,2 \\ comparison\ effective\ between\ \mathcal{Y}_{im}\ \ and\ \mathcal{Y}_{in} \end{cases} \quad (12)$$

2.4.2 Principal component analysis

Multivariate statistics was used in principal component analysis for grouping of the species. Density was used as variable together with wood components, extractives and ash in principal component analysis.

3 Results and Discussion

Scarcity of technical data on chemical composition, calorific value and processing characteristics of traditionally and LU species from Mozambique suggested the need to conduct experiments for obtaining these data. The results reported in the current work are intended particularly to stimulate the use of LU species in order to avert the negative effect of selective logging. Experiments for primary and secondary processing characteristics were only performed for LU species.

3.1 Review on Mozambique timber sector

The review analysed current trends in Mozambique forests derived from inappropriate logging practices. Due to selective logging, a few species are overexploited, even though Mozambique forests comprise around 118 species with potential for commercial use. Therefore, selective logging is eroding ecological diversity and sustainable forest management, and in this way Mozambique runs the risk of forest depreciation with consequent loss of economic growth for the country.

The review compared traditionally used to LU species and found out that there were some similarities (Paper I ;Table 5). The density of metonha fell in the range defined by the densities of chanfuta and jambire, and the corresponding elastic modulus in the range defined by modules of umbila and jambire. Therefore, metonha can substitute chanfuta, jambire and umbila where strength is the main property. Muanga showed a slightly higher density than the well known species, and probably will perform better than these species if strength is the main requisite.

Table 5. *Comparison of density and modulus of elasticity between LU used and well known species*

Physical-mechanical properties	Lesser used species		Well known species		
	Pericopsis angolensis (muanga)	*Sterculia quinqueloba* (metonha)	*Afzelia quanzensis* (chanfuta)	*Pterocarpus angolensis* (umbila)	*Millettia stuhlmannii* (jambire)
Density (kg/m^3)	865	780	670	590	715
Modulus of elasticity (N/mm^2)	-	10 000	13 100	8 412	13 583

Source: Ali *et al.* (2008)

Subsequently, the survey (Paper I) tried to sketch out some solutions to overcome the problems emanated from selective logging by recommending the research on the properties of overlooked species. The knowledge of LU species properties will enable their commercial use, thus alleviating the pressure on traditionally used species.

3.2 Chemical and calorific features

Results in Table 6 show the chemical composition of 8 selected species from Mozambique. Samples were taken along the radial direction of discs from logs cut at breast height. In addition, results at breast height are shown for a disc taken as a whole for metil, since for this species the boundary between sapwood and heartwood is invisible. Chemical experiments of he whole disc were similar to the mean of results along the radial direction (Table 6). Traditional and LU species from Mozambique showed contentof carbohydrate, lignin, extractive and ash in ranges common for tropical species (Paper II; Table 6).

Comparing the contentof cellulose, all species could be divided into 3 groups, the first comprised species with average contents above 40 % (icuria, namuno and umbila), second with average contents in the range of 37-40 % (chanfuta and jambire), and those with average content between 31-37 % (muanga and ntholo, Table 6, Paper II). Hemicellulose in the studied wood species followed a trend similar to that of cellulose. The first group for this polysaccharide comprised species with average contents 12 % (chanfuta, icuria and namuno), second with average contents between 10-12 % (jambire, muanga, and ntholo), and the third group with average contents on the range of 7-10 % (umbila). Peterssen (1984) reported the hemicellulose content of namuno to be 14 %.

Some species showed negligible variations in lignin contents along the radius (chanfuta, icuria, namuno and umbila), whereas other showed large variations in lignin content (jambire, muanga and ntholo, Table 6). Based on average lignin content, the studied species were divided into 3 groups, with average lignin content above 33 % (ntholo), with average lignin content in the range of 26-33 % (chanfuta, jambire, namuno and umbila), and with average lignin content below 26 % (icuria and metil, Table 6). Sapwood of ntholo showed higher lignin content than heartwood of chanfuta, icuria, namuno, metil and umbila (Table 6). According to Peterssen (1984) Klason lignin of namuno is 20 %.

Only acetone soluble extractives were considered in this study. The extractives showed large variations along the radial direction. The extractives showed higher contents in outer and inner heartwood than in sapwood, indicating that sapwood is probably less durable than heartwood (Table 6) whereas icuria showed an inverse trend. Based on extractives content, the studied species comprised 3 groups, with average contents above 7 % (chanfuta, muanga and umbila), with average contents in the range of 3-7 % (jambire, namuno and ntholo), and those below 3 % (icuria and metil). High extractive content raises natural durability. According to Hernádez (2007), woods containing considerable amount of extractives also exhibit less shrinkage. Icuria and metil may therefore exhibit high shrinkage, due to their low extractive content (Table 6).

The studied species demonstrated small variations of ash content along the radius. Based on ash content, the first group of species showed an average ash content above 2 % (chanfuta, metil and ntholo), the second had average ash content between 1-2 % (jambire, muanga and namuno), and the third group was that with an average ash content below 1 % (icuria and umbila, Table 6). Sapwood of ntholo showed higher ash content than all radial locations of the remaining species, except metil (Table 6). Ash content was used as parameter to predict minerals content. High minerals content may be potentially related to poor machining properties.

Similarity of chemical composition and density between jambire and muanga is evident from Tables 5, 6 and 7. Thus, muanga is suitable for similar end uses as jambire. Ntholo and namuno are similar in chemical composition to the most commercially used species, but they differ in density. Metil is similar to umbila in terms of density, but the chemical composition makes metil different than umbila. Icuria has similarity in terms of density with jambire and muanga, but has dissimilarity with regard to chemical composition, particularly the extractive content.

Table 6. *Content of cellulose, hemicellulose, Klason lignin, extractives, ash (wt% db) and density of 8 Mozambican wood species.*

Species	Radial location	Cellulose[a]	Hemicellulose[a]	Klason lignin[b]	Extractives	Ash[a]	Density kg/m³
Chanfuta	S	39.85	13.35	25.38	2.49	2.22	693
	OH	36.75	12.94	26.99	9.92	2.56	800
	IH	38.45	12.41	25..96	9.12	2.54	750
Icuria	S	41.65	16.15	23.81	3.43	0.79	812
	OH	42.20	14.8	24.86	2.20	0.69	973
	IH	38.30	15.38	25.52	1.90	0.83	950
Jambire	S	36.95	12.77	28.93	1.81	1.47	850
	OH	36.80	10.72	34.18	5.62	1.57	922
	IH	37.25	10.68	32.62	4.79	1.58	900
	S	34.00	12.75	29.84	3.82	1.46	830
Muanga	OH	33.60	10.37	34.13	9.83	1.32	920
	IH	34.95	10.44	34.97	8.31	1.23	910
	S	40.30	13.39	24.97	1.10	1.03	1040
Namuno	OH	41.00	13.67	27.14	5.25	0.81	1160
	IH	41.65	12.85	27.37	5.13	0.73	1100
	S	32.55	10.77	30.79	2.59	2.81	1027
Ntholo	OH	30.65	9.83	37.51	4.25	2.74	1136[c]
	IH	30.35	9.9	36.89	3.67	3.46	1100[c]
	S	44.20	8.03	30.48	2.23	0.52	495
Umbila	OH	46.10	7.63	31.10	11.69	0.45	575
	IH	43.55	8.16	30.82	11.69	0.63	540
Metil	Whole	39.37	11.78	21.53	1.98	3.10	600

[a] extractive- free; [b] ash free; [c] Source: Ali *et al.* (2010).

S = Sapwood; OH = outer heartwood; IH = inner heartwood

The mineral content of ash influences the amount of ash produced and consequently the combustion process by forming gaseous and solid emissions and by significantly influencing the ash melting point behaviour as well as fouling and the corrosion process on furnaces walls and in the boiler (Obernberger *et al*. 1997). In addition to these ash related problems, it can also constitute a significant issue regarding the treatment and disposal of generated ash material in an economical and environmental friendly way (Arvelakis & Frandsen 2005).

Analysis of mineral content (Table 7) showed variation between species for all studied minerals. Calcium, potassium and silicon showed highest content among the studied minerals. Particularly important was the discovery that ntholo had silica content slightly higher than 0.5 %. Silica content is one of the factors that affect tool wear. In general, minerals concentrations in the studied species were higher than concentrations found in the literature (Ankonkhai & Nwokoro 1987; Ankonkhai 1988; Mansilla *et al.* 1991). For example, calcium concentration in ntholo was 5.24 times as higher as in *Acacia caven* (Mansilla *et al.* 1991). Correlations between calcium and density suggested by Ankonkhai (1988) were not found in this study. Silica contents, less than 1100 mg /kg (0.11 %) were not traceable.

Table 7. *Mineral contents (wt% db) of selected wood species from Mozambique. Standard deviation (STD) shown in parentheses*

Species	Minerals[b]				
	Cu	Mn	Si	Ca	K
Chanfuta	0.00046	0.00012	0.122	1.026	0.406
	(0.00017)	(0.00005)	(0.049)	(0.090)	(0.213)
Icuria	0.00021	0.00767	0.110	-	-
	(0.000023)	(0.00074)	(0.000)		
Jambire	0.00022	0.0594	0.110	-	-
	(0.00004)	(0.0235)	(0.007)		
Metil[a]	0.00031	0.00029	0.114	0.69	1.07
	(0.00009)	(0.0)	(0.009)	(0.23)	(0.21)
Muanga[a]	0.00040	0.00276	0.110	0.66	0.36
	(0.00011)	(0.00091)	(0.0)	(0.33)	(0.04)
Namuno[a]	0.00017	0.00013	0.124	0.34	0.17
	(0.00003)	(0.00003)	(0.0887)	(0.06)	(0.03)
Ntholo[a]	0.00031	0.00443	0.577	1.55	0.16
	(0.00002)	(0.00164)	(0.140)	(0.90)	(0.03)
Umbila	0.0003	0.00126	0.110	-	-
	(0.00011)	(0.00006)	(0.0)		

[a] Species which underwent cutting forces and tool wear experiments

[b] Concentrations of Sb, B, Al, Fe, Na, As, Pb, P, Ba, Cd, Co, Cu, Cr, Hg, Mo, Ni, V, Sn, Zn, Se, and Ti were smaller than concentrations of Cu and Mn.

The minerals content influencing machinability of species (Si and Ca) were overall in the ranges considered for non-decisive effect (Table 7). The combined effect of silica and calcium content for ntholo may have influenced tool wear in the current study (Table 10) (Paper IV).

The elementary analysis of the studied wood species showed that concentrations of carbon (C), hydrogen (H) and Oxygen (O) were within the ranges reported for deciduous trees (van Loo & Koppejan 2003). The concentration of oxygen, that negatively affects the HHVwas in the range of 40.60-45.2 wt% (db) for all species (Table 8).

Table 8. . *Elementary analyses (wt% db) of hardwood species. The standard deviation (STD) is shown within parentheses.*

Species	Element					
	C	H	N	O	S[a]	Cl
Chanfuta	51.74	5.80	0.16	42.30	0.01	<0.01[b]
	(0.82)	(0.07)	(0.05)	(0.81)		
Icuria	49.67	6.13	0.10	44.10	0.01	<0.01
	(0.23)	(0.06)	(0.00)	(0.17)		
Jambire	52.18	5.76	0.72	41.34	0.01	<0.01
	(0.47)	(0.09)	(0.13)	(0.36)		
Metil	48.50	6.02	0.24	45.24	0.02	0.03
	(0.20)	(0.04)	(0.05)	(0.23)		(0.01)
Muanga	53.02	6.06	0.32	40.60	0.01	0.04
	(0.39)	(0.05)	(0.08)	(0.42)		(0.01)
Namuno	50.62	5.96	0.10	43.32	0.01	0.02
	(0.54)	(0.05)	(0.00)	(0.49)		(0.01)
Ntholo	50.23	5.63	0.10	44.03	0.01	0.07
	(0.41)	(0.14)	(0.00)	(0.35)		(0.01)
Umbila	52.78	5.95	0.13	41.15	0.01	<0.01
	(0.84)	(0.06)	(0.05)	(0.78)		

[a] The STD values were $\leq$ 0.01

[b] Detection limit is 0.01 %

Higher heating values of the studied species were in the range of 19.38-21.50 MJ/kg (db), with the highest value measured in muanga and the lowest in metil (Table 8, Paper III). These results can be correlated with the O concentration which affects negatively the heating value and the concentrations of C and H which contribute positively.

Table 9. *High heating values, volatiles and density of traditionally and LU species from Mozambique*

Species	HHV (MJ/kg)	Volatiles [wt% (db)]	Density kg/m^3
Chanfuta	20.52 (0.05)	76.34 (2.08)	740
Icuria	19.69 (0.20)	82.00 (1.35)	898[a]
Jambire	20.68 (0.15)	74.82 (0.69)	887
Metil	19.38 (0.07)	77.72 (0.76)	627
Muanga	21.50 (0.15)	74.46 (1.06)	865
Namuno	20.13 (0.12)	78.26 (0.92)	1 111
Ntholo	19.99 (0.19)	75.96 (0.81)	896
Umbila	21.12 (0.01)	79.58 (1.59)	536

[a] Source: Ali *et al.* (2010)

The ranking of the species using the FVI (Eq. 1) that takes into account ash content, density and heating value, from the best to the worst was as follows: namuno > icuria > jambire > umbila > muanga > chanfuta > ntholo > metil (Paper III).

Namuno was the best ranked, whereas metil was the worst ranked species. A similar result was obtained by Abbot *et al.* (1997), where muanga was ranked as the best wood fuel and ntholo was one of the worst woodfuel in a study of 15 wood species from Southern Africa.

3.3 Machinability of LU species

Machinability comprised main cutting forces in 90°-90° and 90°-0° directions and tool wear radius. Overall, cutting forces followed the general trend to increase with increasing density (Table 9). The cutting forces ranged from 80.98 N for metil, to 187.50 N for namuno in 90°-90° direction and from 34.17 N to 69.59 N for metil and namuno, respectively, in 90°-0° direction. Tool wear radius was in the interval of 5 μm and 43 μm, for metil and ntholo, respectively (Table 10). The study of tool wearing was based on the effects of physical (density) and chemical features (extractive, ash and silica contents). Experiments on tool wearing showed that the silica content had high effect on tool wear radius (Paper IV).

Table 10. *Density, main cutting forces in 90°-90° and 90°-0° and tool wear radius of lesser used species from Mozambique. Standard deviation (STD) shown in parentheses.*

Species	Density kg/m^3	Cutting forces N		Tool wear radius[a] µm
		$F_{90°-90°}$	$F_{90°-0°}$	
Metil	604 (16)	81 (7)	34 (6)	5 (2.1)
Muanga	926 (14)	117 (8)	51 (4)	15 (4.9)
Ntholo	751 (28)	103 (9)	43 (3)	43 (4.1)
Namuno	1112 (14)	188 (9)	70 (9)	9 (3.9)

[a]Source: Cristovão *et al* 2011

Cutting forces and tool wear radius were used as input variables for calculating the machinability index to rank the species (Paper V). The machinability index was calculated with the aid of digraph and matrix method using Eq. 3 Machinability attribute values (Table 11) were calculated using Eq. 4 and input data from Table 10 (cutting forces and tool wear radius). Relative importance values of machinability attributes were calculated by Eq. 5 and taking into account the approach by Rao & Gandhi (2002) for assignment of relative importance value of tool wear to cutting force $(a_{TCF} = 8)$.

Table 11. *Machinability attribute values* (D_i)

Species	Tool wear radius	Cutting forces 90°-0°	Cutting forces 90°-90°
Metil	10	10	10
Muanga	7.37	5.37	6.57
Ntholo	0	7.41	7.97
Namuno	8.95	0	0

Table 12. *Relative importance values of machinability attributes* (a_{ij})

Attribute	Cutting forces 90°-90°	Cutting forces 90°-0°	Tool wear radius
Cutting forces 90°-90°	-	5	8
Cutting forces 90°-0°	5	-	8
Tool wear	2	2	-

According to ranking using machinability index, the easiest wood species to be machined was metil, corresponding to machinability index of 1730, whereas the most difficult species was namuno, corresponding to machinability index of 303 (Paper V). Namuno was highly penalized by its high cutting forces. There was no similarity between species in terms of machinability. The same held true in Tukey's paired comparison of species using density or cutting forces.

In current work $per(A) = Machinability\,index$, where A is the matrix in Eq. 2

Machinability indexes and ranking:

Metil	1 730
Muanga	788
Ntholo	478
Namuno	303

Table 13. *Values of coefficient of similarity* (C_s) *between species for* $(a^{*}_{TCF} = 8)$

Species	Muanga	Ntholo	Namuno
Metil	0.46	0.28	0.18
Muanga		0.61	0.38
Ntholo			0.63

*a_{TCF}-coefficient of relative importance of tool wear to cutting forces

Considering the coefficient of similarity in Table 13 and the ranking of species recorded above, machinability of muanga, ntholo and namuno, was 46 %, 28 % and 18 % that of metil, respectively when the coefficient of relative importance of tool wear to cutting forces was eight.

3.4 Statistical analysis

Statistical analysis of colleted data from experiments for chemical and machinability features was performed according to the model described by Eq. 8 and Eq. 9. The main aim was to compare the species based on the determined features.

3.4.1 Simple comparative model

A simple comparative model was used for statistical analysis of data from trees of eight species earning Tables 6 and 14. Table 14 shows the p values of five dependent variables at two levels (level of species and level of sample position). Cellulose, hemicellulose, lignin and ash content are significant at the 0.1 % level, and extractive content is significant at 5 % level at the level of species. Ash and cellulose are not significant at the level of sample position. Hemicellulose, lignin and extractive content are significant at 1 % level for sample-position. Thus, for the studied species the content of all wood components could be used to differentiate one species from another. Moreover, contents of hemicellulose, lignin and extractives could be used to identify sample position within each species, whereas cellulose and ash contents could not be used to identify sample position.

Table 14. *P values of wood components for evaluating statistical significance for five trees per species for chanfuta, icuria, jambire, muanga, namuno, ntholo and umbila.*

Variable	Level	
	Species	Sample position
	P Value	
Cellulose	0.0001	0.6026
Hemicellulose	0.0001	0.0062
Lignin	0.0001	0.0017
Extractives	0.0236	0.0033
Ash	0.0001	0.4639

For cutting force statistical analysis, all variables (density, rake–angle and species) were significant at 0.1 % level.

Figure 9 shows box plots of the main cutting force of metil, muanga, ntholo and namuno sorted by species and rake angle in 90°-90° cutting direction at the level of species.

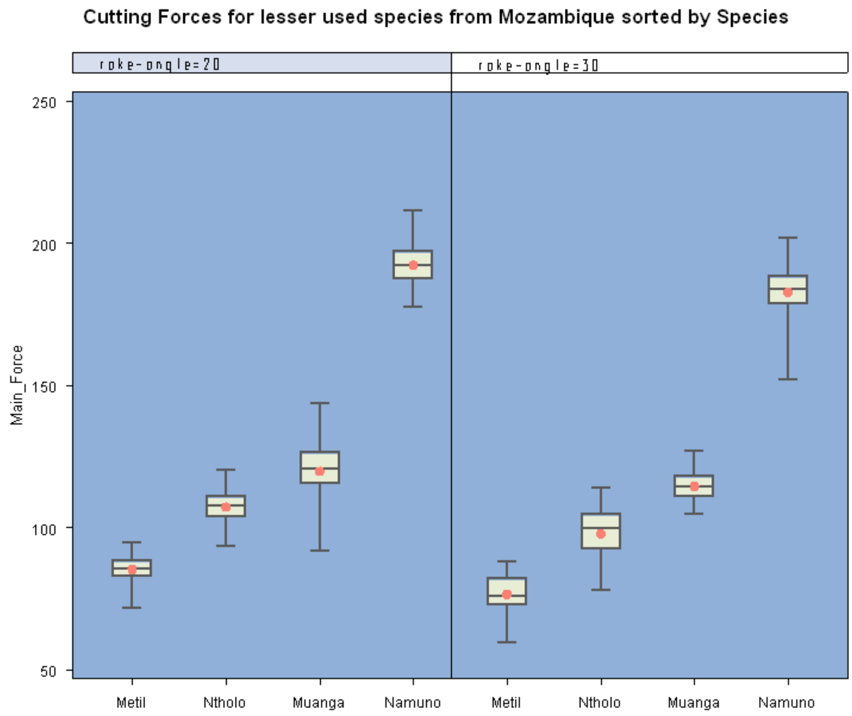

Figure 9. Box plots of cutting forces for LU species sorted by species and rake angle in 90°-90° direction

The rake angle effect can be detected by comparing the species mean measured in each value of rake angle (Figure 9). In Eq. 12 μ was the species mean and α_j the rake angle effect.

3.4.2 Principal component analysis

Principal component analysis was perfomed on the data of Table 6 regarding grouping of species at the level of sample-position. The grouping was as given in Figure 10.

The first three principal components could explain 86.96 % of variability of the data. Since the variables all have different scales, the PCA axes were computed based on the correlation matrix of the specified variables.

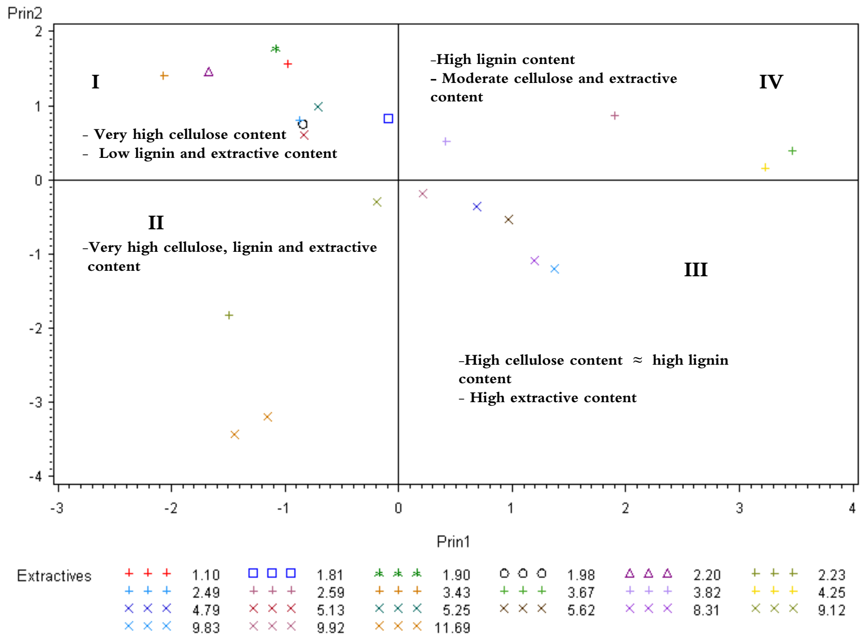

Figure 10. Principal component analysis (Prin2xPrin1) of selected species from Mozambique

First group (I, Figure 10) comprised icuria, metil and namuno (for all sample-positions), chanfuta and jambire(sapwood). This group was characterised by very high cellulose, low lignin and low to moderate extractive content. Regarding density, extractive and ash content there were dissimilarities in the group. Dissimilarities in variables such as density, extarctive and ash content have influenced features such as HHV, machinability and FIV (Table 9). Namuno and icuria were best ranked for FIV owing to their high density and low ash content. Sapwood of chanfuta and jambire would earn similar FVI ranking to that earned by metil due to similarity in ash content and density. Concerning machining, namuno was worst and metil best ranked, mainly due to density effect. According to Antwi-Boasiako *et al.* (2010), natural durability of timber is influenced by its extractive and lignin type, density and anatomy that influences permeability and pH. In this grouping only namuno heartwood has been reported as very durable probably owing to combined effect of density and extractive content (Paper II; Lemmens 2006). This group would fit best for the pulp and paper industry.

Characterisic features for second grouping (II, Figure 10) were very high cellulose, moderate lignin and very high extractive content. This group included umbila (sap-, heartwood)and chanfuta inner heartwood. Another feature would be high natural durability owing to their high lignin and extractive content. Machinability ranking would be high due to their low density, whereas FVI would be poor owing to low density for umbila and high ash content for chanfuta. Umbila has been reported to exhibit low shrinkage (Paper I). Thus, all samples of the grouping are likely to exhibit low shrinkage.

High cellulose, lignin and extractive content characterised the third group (III, Figure 10). In this grouping there were three species, namely muanga, jambire and chanfuta, in outer and inner heartwood for the first two species and in outer heartwood for the last species. A peculiar trend in this group was that the species had aproximate contents of lignin and cellulose, being chanfuta the only species deviating slightly from the trend of the grouping. Another feature of the group was moderate to high extractive content. All the features seem to be indicative for high calorific values (Table 9). Muanga was best ranked regarding HHV.

The last grouping (IV, Figure 10) was characterised by moderate extractive and cellulose content and a lignin content ranging from high to very high. This grouping comprised ntholo for all sample-positions and muanga in sapwood. Ntholo heartwood has been ranked as very durable probably with density and lignin content playing major roles (Paper II). Concerning machinability, the grouping would perform poorly owing to its high density and minerals content (Tables 6,7). Although, the grouping showed high density, it could be poorly ranked in terms of FIV due to its high ash content.

It seemed that the groupings given in Figure 10 were based mainly on cellulose and lignin content.

This section of results and discussion is devoted to aspects that may be related to either chemical composition or physical properties which are not part of current study. One of such aspect is drying of timber that is one of the most important processes in wood product manufacturing. Drying influences the mechanical properties of wood in three ways, namely through the direct effect of moisture loss, the internal drying stresses and strains (Bektha *et al.* 2006).

Theoretically, wood extractives affect transport properties, since they may block not only the macrocapillary pathways such as cell lumens and pits, but also the microcapillary pathways within the cell wall (Chen & Choong 1994).

It has been reported that the diffusion coefficient is influenced by density (Youngman *et al.* 1999). Ntholo has been reported as a species that dries slowly but easily (Uetimane Jr *et al.* 2010), with a diffusion cofficient of 2.4 E-10 m^2/s, for MC in the range of 20-45 %, for both sapwood and heartwood. Owing to their extractive content and density (Table 6), muanga and namuno, may exhibit lower diffusion coefficient than ntholo, the first mainly due to extractive content and the second taking into account its higher density. Moreover, metil may exhibit higher diffusion coefficient instead, owing to its lower extractive content and density.

4 Conclusions

Mozambique timber sector survey argued that the characterising features of the sector were selective logging practices, overexploitation of a few species, poor knowledge of properties of lesser used species and probable depreciation of forests due to selective logging. The review sketched out as solution, research on properties of under used species in order to enlarge the resource base for alleviating the pressure on overexploited species. Taking into account the standing stock volume in the last national inventory, LU species, such as *Acacia nigrescens* Oliv, *Icuria dunensis* Wieringa, *Pseudolachnostylis maprounaefolia* Pax, and *Sterculia appendiculata* K. Schum, were selected for research on chemical, fuel wood and machinability features. Moreover, with the aim to update chemical and fuel wood features of traditionally used species, namely, *Afzelia quanzensis* Welwn, *Milletia stuhlmannii* Taub, *Pterocarpus angolensis* DC and *Pericopsis angolensis* Meeweven were selected and included in the study.

All chemical and fuel wood experiments were performed according to standards methods. Results from experiments on chemical and fuel wood features showed that chemical composition and fuel wood values were in ranges considered normal for tropical species. With regard to comparison of chemical features between well-kown and LU species, this work argued that icuria and metil were different in that they recorded low content of lignin and extractive, whereas namuno and ntholo were similar due to their high content of lignin and extractive. Muanga could be a promising substitute for jambire in all applications owing to similarities in chemical composition and density. Moreover, namuno was best ranked while metil was the worst ranked species in ranking using FIV. Although muanga recorded the highest HHV, it was poorly ranked in terms of FVI owing to its moderate ash content and density. Finally, concerning chemical features, the work concluded that all studied species showed low silica content.

Only LU species were used for machinability. Cutting forces and tool wear measurement were performed with the aid of pertinent equipment. Results from cutting force measurements showed a normal trend with cutting force increase with increasing density. Silica content was the major factor affecting tool wear. In order to obtain net effect of the output variables of machining process on machinability of LU species, digraph and matrix method was used to rank performance of species during cutting.

With experiments on machinability, the work concluded that metil was the easest species to be machined, whereas namuno was the most difficult species. In addition, taking into account the value of measured tool wear radius, metil was best ranked in terms of tool wear, whereas ntholo was worst ranked.

Because of their high density and probable high natural durability and hardness, namuno and ntholo may be used in parquet flooring, wall paneling and other heavy duty applications, both in outdor and indoor situations. Metil may need improvement in its durability owing to its low lignin and extractive content. Metil may find application in the construction industry. Wood from namuno and ntholo may be valuable due its aesthetic appearance, whereas wood from metil showed low aesthetic value.

Statistical analysis using simple comparative model showed that content of hemicellulose, lignin and extractive could be used to identify sample position within each species, whereas cellulose and ash content could not be used to identify sample position.

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