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Original Article

Durability Response of Perishable Wood Species after Pressure Impregnation of Extractives-Based Solutions from Naturally Durable Species of Mozambique

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ABSTRACT

Poor natural durability is a key feature hindering the acceptance of most lesser-used wood species, such as *Brachstegia spiciformis*, *Julbernadia globiflora*, and *Sterculia appendiculata*. Generally, the durability of the aforementioned wood species is improved by impregnating its timber with toxic chemicals contained in standard wood preservatives. In this study, eco-friendly wood preservatives based on extractives sourced from sawdust of naturally durable species such as chanfuta (*Afzelia quanzensis*) and *mecrusse* (*Androstachys jonhsonnii*) were used to treat the group of aforementioned perishable wood species. After pressure treatment, the study assessed the durability responses using standardized in vitro durability test methods against brown rot fungus *Postia placenta* and white rot fungus *Trametes versicolor* (EN 113-1:2018) and changes of compression strength parallel to the grain (ISO 3787). The samples of perishable timber species were impregnated with separated extractives-based preservatives of chanfuta and mecrusse in five concentrations (0.5 mg/mL, 1.0 mg/mL, 1.5 mg/mL, 2.0 mg/mL, and 2.5 mg/mL). A subset of treated samples was leached (SS-EN 84:2020-E) to infer preservative fixation and also exposed to the same wood-destroying fungi. The results showed that both extractive formulations (chanfuta and mecrusse) changed the durability ratings of perishable species. Firstly, the subset of treated and unleached samples of *Brachystegia spiciformis* improved from non-durable to moderately durable, *Sterculia appendiculata* to durable class and *Julbernadia globiflora* samples improved to very durable class; secondly, after leaching, the durability remained unchanged (non-durable class) for *Brachstegia spiciformis* but improved from non-durable to a moderately durable class for both *Julbernadia globiflora* and *Sterculia appendiculata* timber species against *Trametes versicolor*. The compression strength of perishable timber species treated with mecrusse increased and decreased in samples treated with chanfuta. The dosage of both wood extractive formulations did not affect compression strength.

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INTRODUCTION

Mozambique's vast native tropical hardwoods of over 100 wood species represent unmatched potential for timber production. The country's natural forest comprises different types of forest referred to as Miombo (dry and wet), Mopane, and Mecrusse (Magalhães *et al*., 2020). Miombo is the most predominant forest type, occupying two-thirds of the territory (Ribeiro *et al*., 2015). However, over the past years, the growing stock of well-known timber species such as chanfuta (*Afzelia quanzensis* Welw), jambirre (*Milletia stuhlmannii* Taub), and umbila (*Pterocarpus angolensis* D.C.) has substantially declined in Mozambican natural forests (Magalhães *et al*., 2020). The last National Forest Inventory (DINAF, 2018) reported an increase in the allowable annual cut of lesser-used timber species in provinces (e.g., Miombo forest) where the demand is high. Harvesting abundant but lesser-used wood species is gradually encouraged in this context. These lesser-used timber species are known for their poor natural durability, which requires further treatment when exposed to an adverse environment. Perishable wood can be degraded by wood-destroying organisms such as fungi, bacteria, marine borers, and insects (Forest Products Laboratory, 2010; Andres *et al*., 2015).

Most standard wood preservatives have proven to be highly toxic to wood-destroying organisms, providing in-service protection and longevity for wooden constructions. Preservatives based on waterborne (e.g., Chromated Copper Arsenate; CCA) or organic-based chemical preparations (e.g., creosote) are the most effective against a wide range of organisms and are the most used worldwide. They extend service life up to 50 years, even in high-hazard situations (Chirkova *et al*., 2011; Salminen *et al*., 2014; Jones and Brischke, 2017; Barbero-López *et al*., 2020; Broda, 2020). However, the toxicity and detrimental effects on both humans and the environment led to restrictions on its use in many European countries and the USA (Archer and Lebow, 2006).

Nowadays, wood protection methods with less negative environmental impact have been intensively studied. For example, Tascioglu *et al.* (2013) evaluated the antifungal resistance of some commercial and environmentally friendly plant extracts in four different concentrations of mimosa (*Acacia mollissima*), quebracho (*Schinopsis lorentzsis*) and pinus (*Pinus brutia*) bark extracts by impregnating Scots pine (*Pinus sylvestris* L.), beech (*Fagus orientalis* L.) and poplar (*Populus tremulo*) wood species, then exposed to the wood destroying fungi. The results showed that commercial mimosa and quebracho extracts could be utilized as alternative wood preservatives against wood decay fungi. Additionally, Woźniak *et al*. (2022) evaluated the application of caffeine and chitosan-caffeine solutions as an ecological preservative in wood protection and reported antifungal properties for wood protection.

This study presents an alternative approach to toxic chemicals through testing plant-based solution wood preservatives, which is gaining acceptance worldwide. Eco-friendly wood preservatives can be prepared from renewable biomass such as sawdust of naturally durable wood species obtained in sawmills. The extractives are responsible for protection against wood decay organisms in durable wood species. Mohareb *et al*. (2009) investigated the effect of heartwood extractives on *Cupressus lusitanica* on wood durability. The authors found that extractives present in the heartwood are responsible for natural wood protection. Roszaini *et al*. (2016) performed an *in-vitro* decay test on 12 Malaysian hardwood trees as a function of wood density and extractive compounds. They found that the wood extractives highly contributed to improving durability compared to density.

In this study, selected lesser-used and non-durable wood species, namely *Brachystegia spiciformis, Julbernadia globiflora,* and *Sterculia appendiculata,* were impregnated with formulations based on wood extractives extracted separately from chanfuta (*Afzelia quanzensis* Welw) and mecrusse (*Androstachys jonhsonnii* Prain.) sawdust collected in the local sawmills. The main objective was to assess responses to the durability and mechanical properties of the treated perishable wood species with the wood extractive formulation of the two durable timber species. This work more specifically provided valuable insights into the antifungal potential of the two durable timber species against wood-destroying fungi such as brown rot (*Postia placenta*) and white rot (*Trametes versicolor*), offering an eco-friendly solution to enhance the durability of perishable wood species.

MATERIALS AND METHODS

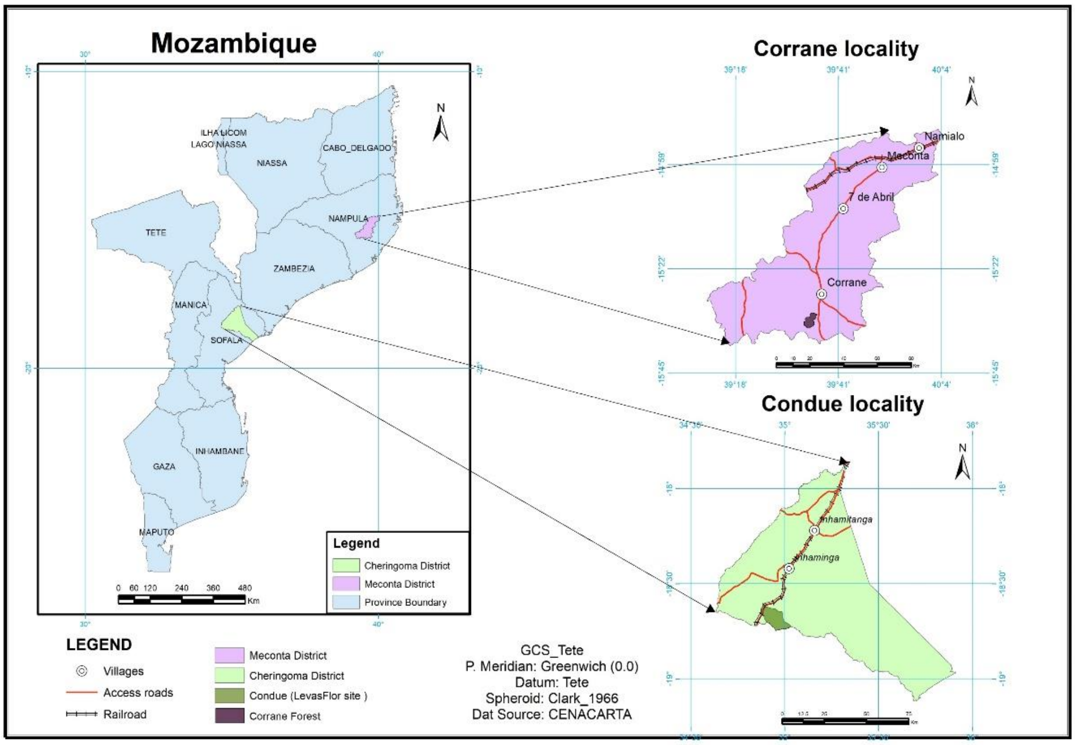
Materials and equipment

Sapwood samples of *Brachstegia spiciformis* (BS), *Julbernadia globiflora* (JG), and *Sterculia appendiculata* (SA); Formulations based on wood-based extractives sourced from sawdust of *Afzelia quanzensis* Welw (AQ) and *Androstachys jonhsonnii* Prain (AJ).

Samples origin

Brachstegia spiciformis and *Julbernadia globiflora* wood samples were collected from humid Miombo natural forests at the LevasFlor Forest Concession in Cheringoma district, Sofala province; meanwhile, *Sterculia appendiculata* wood samples were collected in the natural forests of Corrane locality, Meconta district, Nampula province.

Figure 1: Origin of sampled trees: Cheringoma district, Sofala province and Meconta district, Nampula province.



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Tree selection method

Three mature trees of each lesser-used and non-durable timber, *Brachstegia spiciformis*, *Julbernadia globiflora*, and *Sterculia appendiculata*, were selected from the natural forests of Mozambique (Table 1).

Table 1: Non-durable and lesser-used timber species selected and treated with wood-based extractive solutions

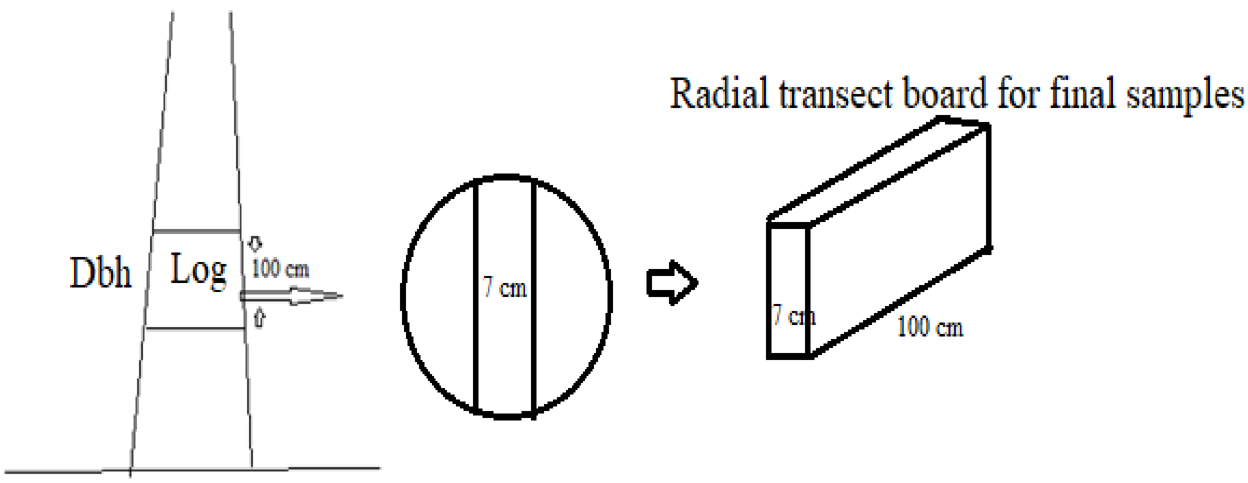
Scientific name	Vernacular name	Family
Brachystegia spiciformis	Messassa	Fabaceae
Julbernadia globiflora	Red messassa	Fabaceae
Sterculia appendiculata	Metil	Malvaceae

Trees of each species were randomly selected based on DBH (minimum 40 cm), stem straightness, and health appearance. Clustered trees were avoided to ensure more variability since tree features vary from place to place. Tree species identity was confirmed at Eduardo Mondlane University through *xylarium* using vouchered reference specimens.

Sample collection and processing

Trees of each species were cut down into logs 1 meter long and converted into planks with 7 cm (rad) x 100 cm (long) in the sawmill (Figure 2). Sapwood samples were taken and processed separately from the planks in the carpentry for the final size of 0.5 cm x 1.5 cm x 4.0 cm for the *in vitro* decay test based on the EN 113-1:2018 standard and 2.0 cm (trans) x 2.0 cm (rad) x 6.0 cm (long) for compression strength parallel to grain as a mechanical property based on ISO 3787 standard.

Figure 2: Sampling procedure diagram in the forest site and sawmill.



Pre-treatment of samples

Before impregnation, a batch of sapwood samples of each lesser-used species in all sample sizes was oven-dried at 105 ± 3ºC for 72 hours and cooled down in a dissecator for 40 min. Then, the initial absolute dry weight was recorded. The samples were re-conditioned to a 12% moisture content in the climate chamber (Temperature: 23ºC; Relative humidity: 75%).

Pressure impregnation of sapwood samples

The sapwood samples of *Brachstegia spiciformis*, *Julbernadia globiflora*, and *Sterculia appendiculata* in two sample sizes were impregnated with two separated formulations, namely one based on extractives of chanfuta and another made from mecrusse extractives following a range of five concentrations, namely: 0.5 mg/mL, 1.0 mg/mL, 1.5 mg/mL, 2.0 mg/mL, and 2.5 mg/mL. More

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specifically, for the sample size of 0.5 cm x 1.5 cm x 4.0 cm, the vacuum (-0.9 bar) was applied for 2 minutes, followed by a positive pressure of 6.0 bars for an hour. Likewise, the vacuum (-0.9 bar) was applied for 5 minutes for sample sizes 2.0 cm x 2.0 cm x 6.0 cm, followed by positive pressure (10.0 bars) for an hour. After releasing the pressure, the samples were left to relax in each liquid for 40 minutes. The vacuum was applied to ensure maximum extractive penetration to the wood structure of the samples.

Post-treatment of sapwood samples

At the end of the treatment, the samples were removed from the impregnation liquid, their weight measured, and left at room temperature for at least a week. Then, the treated sapwood samples from each wood species and concentration were divided into two groups: half were leached, and the other half were kept in the climate chamber (23°C, 75% RH).

Leaching of treated sapwood samples

The leaching process was carried out to simulate the natural weathering in which the treated samples lose antifungal efficiency through moisture. Half of the treated samples were impregnated in distilled water under a vacuum (-0.9 bar for 5 minutes) for a sample size of 0.5 cm x 1.5 cm x 4.0 cm, followed by water immersion for eight days, 10 minutes for a sample size of 2.0 cm x 2.0 cm x 6.0 cm, followed by immersion for 14 days. The water was changed once in two days following the standard SS-EN 84:2020 (E). The samples were separated based on formulation concentration level, species, and source of extractives.

Conditioning of samples before *in vitro* decay test

The samples in both sizes of 0.5 cm x 1.5 cm x 4.0 cm and 2.0 cm x 2.0 cm x 6.0 cm, which included treated and unleached, treated and leached, and control, were kept in a climate chamber at 23°C, 75% RH, to equalize the moisture content (+/-12%) before being exposed to the fungal attack and testing of compression strength parallel to the grain.

***In vitro* decay test**

The *in vitro* decay test was conducted based on standard EN 113-1:2018. More specifically, the test consisted of exposing all subsets of wood samples of perishable species (*Brachstegia spiciformis*, *Julbernadia globiflora*, and *Sterculia appendiculata*), namely: (i) control, reference or untreated, (ii) treated and unleached, and (iii) treated and leached) against brown rot fungus *Postia placenta* and white rot fungus *Trametes versicolor* following a layout in Figure 3. The exposure of wood samples against wood-destroying fungi took place after seven days when the inoculated Petri dishes were fully covered by mycelium. The exposed wood samples were kept in incubators (LMS-cooled incubator 290 L series 3) for eight weeks.

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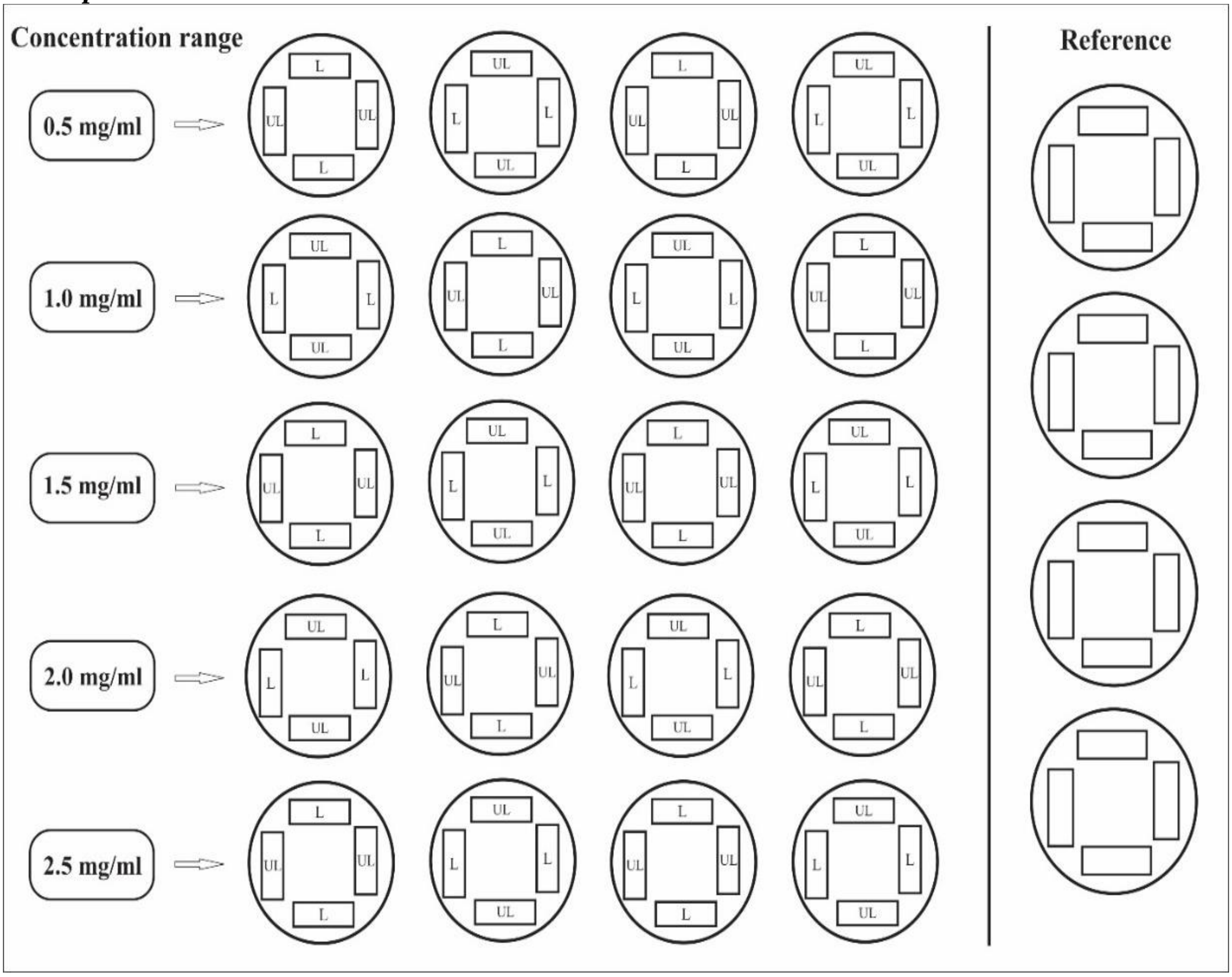
Figure 3: Diagram of the experiment showing concentration levels and exposed treated wood samples arrangement in the Petri dishes, including treated and unleached (UN), treated and leached (L), and control (untreated or reference) samples. The wood-destroying fungi used were *Trametes versicolor* and *Postia placenta*.



Assessment of durability and compression strength changes after pressure treatment

Durability assessment

The durability response was measured by comparing the mean mass losses of treated sapwood samples, treated and leached sapwood samples, and control sapwood samples (untreated condition). The control samples measure natural durability, and the treated samples measure the treatment's response to improved durability, as well as the subset of treated and leached sapwood samples. The changes were reported according to the durability classes as per the corresponding mass loss following formula (1) (EN 113-1:2018).

$$Mass\ loss = \frac{m0-m3}{m0} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where m_0 is the initial dry mass before impregnation, m_3 is the absolute dry mass after incubation.

The calculated mass loss based on the wood species, formulation, and concentration was compared to the durability class based on X values derived from mass loss (Table 2). The improvement from the natural durability rating measured from the control samples after treatment with extractives-based formulations was assessed. Therefore, all changes or durability responses were benchmarked to the natural durability class.

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Table 2: Durability classes based on mass loss

Durability class (DC)	Description	X value (EN 350:2016)
1	Very durable	X ≤ 0.10
2	Durable	0.10 < X ≤ 0.20
3	Moderately durable	0.20 < X ≤ 0.45
4	Slightly durable	0.45 < X ≤ 0.80
5	Not durable	X > 0.80

Source: CEN-EN 350 (2016)

Legend: The X value is equal to the average corrected mass loss of test specimens divided by the average mass of control specimens.

Compression strength parallel to grain

The sapwood samples for compression strength were divided into two groups based on species and concentration level: half carried out the leaching test based on the SS-EN 84:2020 (E) standard, and the other half was kept in the climate chamber (23°C, 75% HR) for further steps. The treated and unleached, treated and leached, and control (untreated) samples of each wood species were performed for compression strength parallel to grain test using the universal material testing machine based on the standard ISO 3787. The means compression strength of control samples for each species was compared to unleached and leached samples. Compression parallel to the grain is a mechanical property which was meant to assess how the strength property will be affected by the entire fixation and leaching of the test samples by wood extractive formulations.

Data analysis

The effect of the formulations based on extractives of chanfuta and mecrusse on wood material biodegradation and compression strength was evaluated using ANOVA (One-way analysis of variance) in a completely random design. The R software was used for data analysis, and the collected data underwent a thorough check for a normal distribution, ensuring the reliability of the results.

The mean values of mass loss and compression strength of the lesser-used and perishable species based on concentration levels and treatments (the treated and unleached, treated and leached, and control) were compared using the LSD test. Therefore, the mean values obtained regarding wood deterioration and compression strength were pair-wise compared to the control samples (untreated condition) to depict durability responses after treatment.

RESULTS AND DISCUSSION

Durability responses after treatment as expressed by mass loss

For all three perishable wood species (*Brachystegia spiciformis, Julbernadia globiflora* and *Sterculia appendiculata*), the results show that after treatment at higher concentration levels (in both wood preservative formulations of chanfuta and mecrusse), the fungal activity of *Trametes versicolor* and *Postia placenta* were reduced significantly as summarised in Table 3 and Table 4. The recorded responses could potentially indicate the presence of an effective active ingredient from extractives of the two naturally durable tropical species (chanfuta and mecrusse).

Durability of treated samples against white rot fungus (*Trametes versicolor*)

Table 3 summarises the durability response of the three perishable wood species treated with chanfuta and mecrusse extractive-based preservatives after exposure to *Trametes versicolor*.

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Table 3: Means of mass loss of wood species treated with both formulations AQ and AJ after eight weeks of exposure to *Trametes versicolor*

Extractives source	Concentration range (mg/mL)	Wood species – Mass loss (%)								
		Brachystegia spiciformis			***Julbernadia globiflora***			***Sterculia appendiculata***		
		C	**UN**	**L**	**C**	**UN**	**L**	**C**	**UN**	**L**
	0	30.8 (6.3)	-	-	25.9(5.6)	-	-	30.5 (3.6)	-	-
Chanfuta (AQ)	0.5		13.6 (3.5) a	39.2 (15.9) f		13.0 (3.0) k	19.8 (2.9) t		8.2 (5.3) t	11.2 (7.4) d
	1.0		13.5 (3.2) a	22.8 (9.0) g		9.3 (3.1) l	13.8 (2.6) k		14.8 (3.0) f	22.8 (4.3) j
	1.5		11.9 (2.0) a	26.2 (14.1) h		6.6 (2.0) m	10.0 (1.2) t		14.9 (4.0) f	22.5 (6.0) j
	2.0		6.2 (1.8) b	20.3 (3.1) g		6.0 (2.1) m	11.1 (1.2) t		8.2 (2.6) l	21.1 (7.8) j
	2.5		6.0 (1.4) b	27.9 (3.0) h		3.7 (2.1) n	7.5 (1.0) p		5.2 (1.0) l	12.2 (3.8) d
						-			-	
	0.5		16.4 (2.9) c	20.6 (5.9) s		11.4 (9.0) p	16.8 (2.2) s		20.3 (4.7) u	32.5 (12.3) f
Mecrusse (AJ)	1.0		17.7 (3.9) c	21.1 (9.6) j		10.2 (7.4) pd	12.6 (1.9) s		14.6 (1.5) i	16.5 (7.7) w
	1.5		15.5 (3.0) d	22.3 (9.1) j		8.9 (2.3) d	9.3 (1.6) t		11.2 (3.0) k	13.3 (6.5) w
	2.0		14.9 (2.5) d	22.3 (7.8) j		4.9 (2.5) q	5.5 (2.4) t		11.6 (5.0) k	13.5 (2.3) w
	2.5		8.9 (2.9) e	23.1 (9.3) j		4.0 (2.6) q	5.0 (1.8) t		6.9 (0.9) v	7.2 (1.8) r

Legend: **AQ -** *Afzelia quanzesis* (chanfuta) extractives source; **AJ -** *Androstachys jonhosonnii* (mecrusse) extractives source;
C- control (untreated samples); **UN -** unleached samples; **L -** leached samples; **ML-** Mass Loss.

Note: Means of Mass Loss variable followed by the same letters do not statistically differ using the LSD test ($p<0.05$).

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The results from Table 3 show that the durability of treated wood samples improves with increased concentration dosage of wood extractive formulations. After treatment with chanfuta extractives formulation using the lowest concentration of 0.5mg/mL, the wood samples of *Brachystegia spiciformis* suffered an ML of 13.6%, which led to a moderately durable class. However, the leached samples revealed a threefold ML increase of 39.2%, reversing to its original non-durable class, inferring poor preservative fixation in the treated wood structure. Likewise, the samples treated with the highest concentration of 2.5mg/mL suffered an ML of 6.0%, improving the durability to the durable class. However, the ML increased to 27.9% after leaching, reversing the timber species to its original durability class of non-durable timber. Lebow (1992) explained fixation as a series of chemical reactions in which the preservative is retained in the wood structure during the service life. However, the interaction with wood components may take days, weeks, or months to be completed. Manhiça *et al*. (2023) stated that the main challenge of impregnating extractives from durable wood species is its fixation or immobilisation into the cell wall. Therefore, chemical compound fixation into wood cell walls is essential and needs special attention (Barbero-López *et al*., 2020). Liibert *et al*. (2011) suggested the fixation of chemical compounds in wood protection systems by combining wood protection agents and oil treatment with hydrophobic properties. According to Hassan (2017), plant oils can reduce leaching by reducing moisture uptake and protecting wood against microbiological organisms by making a surface layer. Augustina *et al*. (2023) stated that the impregnated oil in wood material does not bond with the cell wall but fills the lumen, limiting the water uptake.

A different response was observed for *Julbernadia globiflora*. For example, the treated samples with chanfuta extractives formulation using the lowest concentration of 0.5mg/mL suffered an ML of 13%, improving the durability from non-durable to slightly durable. The subset leached samples increased the ML to 19.8% but retained the previously gained durability of slightly durable, which infers that even after washing out, the impregnated chemical compounds retained their antifungal activity in the wood structure. Additionally, *Julbernadia globiflora* samples treated with the highest concentration of chanfuta extractives (2.5mg/mL) recorded an ML of 3.7% and improved its durability class to durable timbers, but after the leaching process, the ML increased to 7.5%, falling to moderately durable timbers which is still a positive response from its original natural durability class. From its natural durability, *Julbernadia globiflora* timber improved significantly after being treated with the highest concentration, i.e., reaching the durable class. Nevertheless, the protection effect was moderately lost after leaching as the timber dropped to moderately durable.

Meanwhile, *Sterculia appendiculata* samples treated with chanfuta extractives-based formulation using the lowest concentration (0.5mg/mL) suffered an ML of 8.2%, improving the durability to a moderately durable class. Then, after the leaching process, the ML in the same concentration increased to 11.2%, but the durability class remained unchanged, which is also a positive response from its original durability class. Moreover, at the highest concentration (2.5mg/mL), the measured ML was 5.2%, improving the durability class to the durable class. However, the ML increased to 12.2% after leaching, reducing the gained durability to a moderately durable class.

In terms of optimal concentration dosage, no significant difference in ML was observed between the 2.0 mg/mL (6.2%) and 2.5mg/mL (6.0%) of treated samples with the chanfuta extractives formulation, even after the leaching process. Therefore, 2.0 mg/mL is an optimal concentration to slow down significantly *Trametes versicolor* from degrading *Brachystegia spiciformis*. Furthermore, 2.5 mg/mL could be prescribed for both extractive formulations to slow down significantly *Trametes versicolor* from degrading *Julbernadia globiflora* and *Sterculia appendiculata* wood species.

According to Table 3, the samples of *Brachystegia spiciformis* treated with mecrusse extractives formulation at the highest concentration (2.5mg/mL) suffered an ML of 8.9%, improving to a moderately durable class. After the leaching process of a subset of the same concentration, the ML increased by 23.1%, falling to a slightly durable class, a modest improvement from its natural durability.

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Regarding *Julbernadia globiflora*, the measured ML after treatment with the highest concentration (2.5mg/mL) was 4%, improving to durable class. The measured ML of leached subset samples increased to 5% but maintained the gained durability, implying that compounds were fixed in the wood structure, protecting the wood against the fungal attack. A similar response was recorded for *Sterculia appendiculata* samples treated with the highest concentration (2.5mg/mL). The recorded ML was 6.9%, achieving durable class, and after leaching a subset of treated samples, the ML increased slightly (7.2%) but remained unchanged in the durable class. The formulation efficiently protected the two wood species (*Julbernadia globiflora* and *Sterculia appendiculata*) against the fungal attack of *Trametes versicolor*, especially when treated in higher concentration formulation, and the lower ML is potentially a function of bioactive compounds fixation.

The chemical compounds from mecrusse extractives formulation with bioactive action could have interacted with wood components of *Sterculia appendiculata* and *Julbernadia globiflora*, causing them to be retained during the leaching process. Conversely, *Brachystegia spiciformis* recorded poor fixation performance. Although Oyen and Louppe (2012) reported that the sapwood of *Brachystegia spiciformis* is successfully treated with prolonged pressure, the wood species did not retain the bioactive compounds after the leaching process. In turn, Uetimane *et al.* (2009) described *Sterculia appendiculata* timber as easy to treat, meaning it possesses high impregnability due to wide vessels allowing efficient movement of liquids. In fact, Dinwoodie (2000) stated that hardwoods characterised by large diameter vessels have higher permeability and are thus easy to impregnate with liquids. Nevertheless, fixation has been linked to the interactions of impregnated extractives with wood components.

Table 3 shows no significant difference between the 2.0 mg/mL (4.9%) and 2.5mg/mL (4.0%) concentrations of treated samples with the chanfuta extractives formulation, even after the leaching procedure comparing 2.0 mg/mL (5.5%) and 2.5mg/mL (5.0%) concentrations. However, 2.0 mg/mL is an optimal concentration of mecrusse extractives formulation to significantly slow *Trametes versicolor* from degrading *Julbernadia globiflora*. Likewise, 2.5 mg/mL is considered an optimal concentration for mecrusse extractives formulation to slow down *Trametes versicolor* significantly and protect *Brachystegia spiciformis* and *Sterculia appendiculata*.

Durability of treated samples against brown rot fungus (*Postia placenta*)

Table 4 shows a similar durability response trend against brown rot fungus *Postia placenta*, in which the increased concentration of both formulations reduced the fungal growth as expressed by ML.

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Table 4: Means of mass loss of wood species treated with both formulations AQ and AJ after eight weeks of exposure to *Postia placenta*

Extractives source	Concentration range (mg/mL)	Wood species / Mass loss (%) *Brachystegia spiciformis*			*Julbernadia globiflora*			*Sterculia appendiculata*		
		C	**UN**	**L**	**C**	**UN**	**L**	**C**	**UN**	**L**
Chanfuta (AQ)	0	32.1 (8.1)	-	-	25.7 (2.1)	-	-	30.9 (2.2)	-	-
	0.5		41.9 (10.5) e	43.4 (12.0) p		17.9 (2.1) u	31.8 (12.2) u		15.5 (6.3) g	18.1 (5.1) h
	1.0		15.6 (6.3) d	29.2 (13.1) jp		11.4 (1.2) e	19.3 (3.5) s		9.9 (3.1) j	17.9 (2.3) h
	1.5		8.1 (2.9) cd	30.7 (4.1) p		8.1 (2.5) e	12.1 (2.6) m		7.9 (3.5) bj	13.2 (2.2) ht
	2.0		5.4 (2.5) b	10.0 (3.4) j		4.8 (2.1) b	9.4 (2.4) m		6.7 (2.3) b	10.2 (2.2) ht
	2.5		5.1 (2.6) ab	10.2 (2.2) j		1.4 (2.0) b	7.9 (1.1) m		5.5 (1.4) b	6.9 (1.2) t
				-			-		-	
Mecrusse (AJ)	0.5		10.6 (3.6) k	18.1 (3.4) h		9.4 (6.5) t	13.4 (1.3) n		17.2 (2.5) q	32.5 (16.2) p
	1.0		11.5 (3.8) k	15.8 (2.8) q		8.2 (5.6) t	8.8 (2.1) p		13.8 (1.6) bq	15.6 (6.5) g
	1.5		67 (2.3) r	22.5 (3.5) h		6.8 (2.8) t	7.2 (2.2) kp		9.8 (2.5) ybq	15.5 (3.4) g
	2.0		6.1 (2.9) r	12.4 (2.8) q		1.8 (2.9) c	5.8 (2.6) kp		6.5 (2.3) f	21.7 (2.3) g
	2.5		5.2 (2.5) x	10.5 (2.7) j		0.8 (2.5) c	4.8 (1.7) k		6.0 (1.3) f	11.3 (2.6) j

Legend: **AQ -** *Afzelia quanzesis* (chanfuta) extractives source; **AJ -** *Androstachys jonhosonnii* (mecrusse) extractives source;
C- control (untreated samples); **UN -** unleached samples; **L -** leached samples; **ML**- Mass Loss.

Note: Means of mass loss variable followed by the same letters do not statistically differ using the LSD test ($p<0.05$).

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Moreover, according to the results from Table 4, chanfuta extractives-based formulation did not protect the treated samples of *Brachystegia spiciformis* at the lowest concentration of 0.5mg/mL compared to control samples (32.1%), as the ML increased to 41.9%, remaining in its natural durability class even after leaching the samples (43.4%). However, samples treated with the highest concentration of 2.5mg/mL recorded an ML of 5.1%, significantly improving the durability to a durable class. After leaching (10.2%), the timber durability fell to a moderately durable class. A similar response was observed for *Julbernadia globiflora.* For example, the ML recorded (17.9%) for samples treated by the lowest concentration (0.5mg/mL) but still improved the durability to a slightly durable class. After leaching, the ML increased significantly to 31.8%, and the timber durability was reversed to a non-durable class. Furthermore, after treating samples with 2.5mg/mL, the ML was only 1.4%, which allowed the timber to change to a very durable class. After leaching, the ML increased to 7.9%, downgrading its durability to a moderately durable class, which is still an improvement from the original durability class.

Chanfuta extractives formulation did not protect both species (*Brachystegia spiciformis* and *Julbernadia globiflora*) against decay from *Postia placenta* at the lowest concentration, especially after the leaching procedure, inferring poor fixation. The bioactive compounds impregnated at the lowest concentration were easily washed out. Nevertheless, both timber species at the highest concentration fell in the moderately durable class after the leaching procedure, showing resistance to bioactive compounds being washed out through moisture.

Regarding *Sterculia appendiculata,* the treated samples at the lowest concentration exhibited an ML of 15.5%, improving the durability to a slightly durable class. After the leaching process, no change in durability was observed, and the timber species remained in the same class. At the highest concentration of chanfuta extractives formulation, durability was significantly improved to a durable class linked to an ML of 5.5%. However, after the leaching test, the ML slightly increased to 6.9%, and the timber species lost its durability to a moderately durable class. This finding is positive for the species and indicates adequate fixation of bioactive compounds from chanfuta extractives.

Dosage-wise, the results show no significant differences between the 2.0mg/mL (5.4%) and 2.5mg/mL (5.1%) concentrations of treated samples with the chanfuta extractives formulation, even after the leaching process, which recorded ML of 10.0% for 2.0 mg/mL, 10.2% ML for samples treated at 2.5mg/mL. Thus, 2.0mg/mL was the optimal concentration level to slow down significantly *Postia placenta* from degrading *Brachystegia spiciformis* timber. A similar trend was recorded for *Julbernadia globiflora* and *Sterculia appendiculata*, in which 2.0mg/mL was the optimal concentration level to slow down *Trametes versicolor* (Table 4).

The recorded ML of treated samples of *Brachystegia spiciformis* with mecrusse extractives formulation using the lowest concentration of 0.5mg/mL was 10.6%, improving the timber species to a moderately durable class. After the leaching, the ML increased to 18.1%, reducing its durability to a slightly durable class. Furthermore, at the highest concentration (2.5mg/mL), the measured ML was 5.2%, falling to durable class, a statically significant improvement. The leaching procedure almost doubled the ML (10.5%), downgrading the durability to a moderately durable class. The same trend is observed for *Sterculia appendiculata* samples treated at the highest concentration (2.5mg/mL), in which the recorded ML (6%) almost doubled after leaching (11.3%), ending up with a moderately durable class. However, the moderately durable class is unsuitable for most outdoor applications. In fact, according to Ali *et al*. (2011), this timber species is not durable and needs treatment for outdoor applications. In the present study, conversely, the treated samples of *Sterculia appendiculata* at the lowest concentration recorded an ML of 17.2%, improving the durability to a slightly durable class. However, the leaching process caused the ML to increase to 32.5%, reversing the timber species to its natural, non-durable class.

Regarding *Julbernadia globiflora*, the ML of treated samples at the lowest concentration dropped to 9.4%, improving the durability to a moderately durable class, and no change in durability was observed after the leaching procedure. At a 2.5mg/mL concentration,

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the ML was 0.8%, improving the durability to a very durable class. After the leaching procedure, the ML increased six times (4.8%) and moved the timber to a durable class. The bioactive compounds from mecrusse extractives did not leach out through moisture, inferring good fixation in the wood structure of *Julbernadia globiflora*. Lima *et al*. (2021) stated that wood extractives' leaching resistance depends on how they are crosslinked to wood components. Additionally, those extractives can react with cell wall components, forming insoluble complexes resistant to leaching depending on how crosslinked to wood components. Additionally, wood preservative's physical and chemical properties significantly influence leaching resistance. Therefore, the way the wood preservative penetrates the wood by cross-linking reactions between functional groups of the preservative and chemical components of wood has a more significant influence (Bahmani *et al*., 2016). Authors such as Bahmani *et al*. (2016) and Meena (2022) support the idea that wood preservatives should be highly toxic to fungi and resistant to leaching into the environment as part of the requirements for good performance. Depleting the chemical compounds in treated wood might negatively affect the environment and reduce the service life of treated timber (Sabiha *et al*., 2015).

Based on the results from Table 4, no significant difference exists between the 2.0 mg/mL and 2.5mg/mL concentrations of treated samples with the chanfuta extractives formulation, even after the leaching procedure. Therefore, 2.5mg/mL is the optimal concentration level to slow down the fungal activity of *Postia placenta* attacking *Brachystegia spiciformis* and *Sterculia appendiculata* wood species, except for *Julbernadia globiflora* wood species, which is 2.0mg/mL.

Overall durability response against brown rot and white rot fungi

Table 5 summarises the overall durability response against brown rot and white rot fungi as it fits in different durability classes after treatment and leaching of the three perishable wood species using the highest concentration of both wood preservative formulations.

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Table 5: Durability response of perishable species of treated and leached samples against brown rot and white rot fungi

Wood species		***Brachystegia spiciformis***		***Julbernadia globiflora***		***Sterculia appendiculata***	
Wood destroying fungi		TV	PP	TV	PP	TV	PP
Durability response	Chanfuta formulation	Not durable class	Moderately durable class	Moderately durable class	Moderately durable class	Moderately durable class	Moderately durable class
	Mecrusse formulation	Slightly durable class	Moderately durable class	Durable class	Durable class	Durable class	Moderately durable class

Legend: **TV-***Trametes versicolor*; **PP-***Postia placenta*

In general, mecrusse formulation treated and leached samples of *Julbernadia globiflora* and *Sterculia appendiculata* timber species had better durability response against *Trametes versicolor* and *Postia placenta.*

Changes in compression strength parallel to the grain

In this study, the compression strength response after treatment of perishable wood species with separate concentrations of chanfuta and mecrusse sawdust extractive formulations is summarised and discussed in Table 6 and Table 7. Jitkaur *et al*. (2015) stated that the compression strength test examines the mechanical change of wood under longitudinal load and is helpful for structure design. The control samples' compression strength represents the

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reference. The results revealed no significant difference between concentration levels for extractive formulations and compression strength in all perishable wood species (Tables 6 and 7). Indeed, the concentration dosage did not affect the compression strength. However, there is a significant difference in compression strength between control (untreated) and treated and unleached samples from *Brachystegia spiciformis*, *Julbernadia globiflora* and *Sterculia appendiculata* timber.

The treated samples with chanfuta extractives formulation showed slightly higher compression strength values than the control samples, which increased by roughly 5% for all wood species (Table 6). The treatment improved the compression strength of tested timber species. The finding was expected and conquered by Villante *et al*. (2013), who determined the effect of compression strength from *Pinus sylvestris* treated with a light organic solvent preservative. The results showed that the compression strength of treated samples increased 19.2% compared to the control samples. However, the opposite results trend was observed in treated samples with mecrusse extractive formulation (Table 7), where the compression strength was lower than the control. The finding was not unexpected once chemical compounds were impregnated in wood cell structures. Furthermore, after the leaching procedure of treated samples, the results show that the leached samples exhibited lower compression strength values. The finding is in agreement with Yildiz and Kerimoglu (2020), who assessed the effect of leaching on some of the physical and mechanical properties of chestnut wood (*Castanea sativa*) and found that the compression strength decreased due to the leaching process in laboratory conditions.

Table 6: Means of compression strength of treated wood species with chanfuta extractives and leached

Extractives source	Concentration range (mg/mL)	Wood species								
		Compression strength (N/mm^2)								
		Brachystegia spiciformis			*Julbernadia globiflora*			*Sterculia appendiculata*		
		C	UN	L	C	UN	L	C	UN	L
	0	59.3 (2.5)	-	-	63.0 (5.2)	-	-	46.8 (8.2)	-	-
	0.5		61.64 (7.5) a	57.87 (6.3) e		65.42 (6.4) b	60.08 (7.9) f		45.24 (9.2) c	45.18 (5.0) g
Chanfuta (AQ)	1.0		63.34 (6.0) a	58.61 (7.3) e		69.47 (8.7) b	62.31 (6.2) f		47.73 (4.1) c	40.69 (10.1) g
	1.5		61.04 (7.0) a	56.74 (7.0) e		67.21 (6.7) b	54.13 (5.1) f		51.91 (11.1) c	47.70 (3.8) g
	2.0		62.14 (6.0) a	53.95 (7.1) e		67.82 (5.7) b	61.03 (6.2) f		52.14 (12.5) c	43.95 (8.0) g
	2.5		61.13 (7.2) a	49.90 (12.6) e		67.32 (7.6) b	54.92 (11.5) f		54.33 (10.8) c	43.11 (5.1) g

Legend: **AQ -** *Afzelia quanzesis* (chanfuta) extractives source; **C-** control (untreated samples); **UN -** unleached samples; **L -** leached samples.

Note: Means of mass loss variable followed by the same letters did not statistically differ using the LSD test ($p<0.05$).

Table 7: Means of compression strength of treated wood species with mecrusse extractives and leached

Extractives source	Concentration range (mg/mL)	Wood species								
		Compression strength (N/mm^2)								
		Brachystegia spiciformis			*Julbernadia globiflora*			*Sterculia appendiculata*		
		C	UN	L	C	UN	L	C	UN	L
	0	60.8 (6.5)	-	-	68.0 (8.2)	-	-	43.4 (4.2)	-	-
	0.5		48.29 (6.0) c	45.94 (5.2) h		59.04 (7.4) p	58.14 (7.6) l		36.76 (3.7) d	30.95 (5.2) j
Mecrusse (AJ)	1.0		48.55 (6.0) c	45.63 (5.9) h		66.35 (6.2) p	62.27 (7.0) l		37.29 (4.0) d	32.31 (4.2) j
	1.5		52.65 (6.0) c	44.98 (4.6) h		56.66 (6.4) p	55.16 (7.4) l		35.78 (4.3) d	31.80 (4.9) j
	2.0		49.43 (5.9) c	46.50 (3.6) h		67.52 (7.4) p	63.61 (7.3) l		36.02 (4.7) d	33.36 (3.4) j
	2.5		50.71 (5.7) c	48.05 (4.6) h		55.45 (10.3) p	52.13 (6.9) l		39.03 (3.6) d	36.02 (4.5) j

Legend: **AJ -** *Androstachys jonhosonnii* (mecrusse) extractives source; **C-** control (untreated samples); **UN -** unleached samples; **L -** leached samples.

Note: Means of mass loss variable followed by the same letters did not statistically differ using the LSD test ($p<0.05$)

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The results revealed a statistical difference between extractive formulation types impregnated in wood samples for all timber species. The wood samples with chanfuta formulation exhibited greater compression strength in all wood species than those with mecrusse (Tables 6 and 7). For instance, regarding *Brachystegia spiciformis*, in treated wood samples with 0.5 mg/mL of concentration using chanfuta extractives formulation, the compression strength was 61.64 N/mm^2. Therefore, in the treated wood samples with mecrusse extractives formulation at the same concentration, the compression strength decreased to 48.29 N/mm^2. The finding was also observed in *Julbernadia globiflora* and *Sterculia appendiculata* timber.

CONCLUSIONS

Based on the results, it can be concluded that both wood extractive formulations of chanfuta and mecrusse responded positively by changing and improving the durability rating of all three perishable wood species of *Brachystegia spiciformis, Julbernadia globiflora* and *Sterculia appendiculata.* The leached subset of wood samples treated with chanfuta and mecrusse extractive formulations improved durability from non-durable to slightly durable for *Brachstegia spiciformis*, moderately durable class for both *Julbernadia globiflora* and *Sterculia appendiculata* timber species.

In contrast, the unleached samples improved durability from non-durable to moderately durable for *Brachstegia spiciformis*, durable for *Sterculia appendiculata* and very durable class for *Julbernadia globiflora* timber species. Adequate fixation of extractive formulation in non-durable timbers minimises leaching, therefore protecting the environment from chemical pollution. The compression strength of all perishable timber species treated with mecrusse increased and decreased in samples treated with chanfuta. The dosage of both wood extractive formulations did not affect compression strength.

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