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Visite des essais de durabilité des bois en conditions extérieures, sur la station de recherche de South Johnstone (Queensland, Australie) du ministère de l'agriculture et de la pêche du Queensland (DAF), lors de la conférence annuelle IRG54 (mai 2023) de l'International Research Group on Wood Protection (IRGWP).
Visit to wood durability field tests, at the Queensland Department of Agriculture and Fisheries (DAF) research station in South Johnstone (Queensland, Australia), during the IRG54 (May 2023) annual meeting of the International Research Group on Wood Protection (IRGWP).
Photo K. Candelier

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ÉDITORIAL

ARTICLES SCIENTIFIQUES

DESCRIPTIF TECHNIQUE

RÉSUMÉ DE THÈSE

VOS LECTURES

ACTES DE CONFÉRENCE

CONFÉRENCES INTERNATIONALES

Bois et Forêts des Tropiques – ISSN: L-0006-579X
Volume 358 – 4rd quarter – December 2023 – p. 1-2
CONTENTS

EDITORIAL

SCIENTIFIC ARTICLES

TECHNICAL DESCRIPTION

PHILOSOPHIÆ DOCTOR ABSTRACT

BOOK REVIEW

CONFERENCE PROCEEDINGS

INTERNATIONAL CONFERENCES

IRGWP: An international network of key players for a better understanding and industrial developments in wood protection and preservation

Wood durability around the world in a global climate change context

Wood has long been one of the world's primary building materials, and it remains so today despite competition from alternative materials (e.g., PVC, fiberglass, concrete). Worldwide wood consumption is on the rise, and this trend is set to continue, given the growing importance of the bioeconomy (FAO 2022). This rising demand for wood to provide local construction materials with a low environmental impact is all the more pronounced in the southern countries, where demographic growth is high. In response to higher wood consumption, the area occupied by forest plantations is increasing in most developed countries, while deforestation in tropical parts of the world is still of serious concern (Fisher et al. 2020).

In most tropical countries, with large forest areas and great diversity in terms of wood species, local timber production generally only focuses on a few abundant species (associated with a long renewal period) and only values the old large-sized trees (with a diameter greater than 50 cm). In the context of growing needs for timber, such a restrictive value chain may exacerbate pressure on tropical forest ecosystems. It is therefore essential to broaden our knowledge about the potential to use more species and lower-quality logs for timber production. Tropical rainforests currently cover 1,070 million hectares of the world's surface (90% of them are located in Central Africa, South America, and Southeast Asia), with more than 50,000 timber species, but only a handful of these are used (figure 1). It is estimated that 400 million hectares of these forests are currently given over to timber production. However, research over many decades has shown that the regulations that govern timber harvesting in tropical forests – currently based on logging intensity and cutting cycle – do not allow for the long-term recovery of the timber volume being harvested from these ecosystems. It is therefore urgent that we seek out new sources of timber (Putz et al. 2012).

Many types of wood are overlooked in the international market today, as the demand lies with the more well-known types of timber species. It is therefore important to consider alternative options and choose wood according to the qualities and characteristics required to meet targeted end-use applications.

In numerous tropical forest species, wood properties are poorly described, and wood is undervalued. At the same time, to maximise yield, foresters often apply intensive silvicultural management to fast-growing tree species, resulting in wood with wide growth rings, lower wood density, a lower proportion of heartwood, and, in many cases, lower wood durability (Kojima 2009).

Wood protection refers to measures that, in various ways, aim to improve the resistance of wood and wood-based materials to biodegradation and biodeterioration. Such organisms include wood-decaying fungi, termites, and other wood-destroying insects, marine borers, and discolouring microorganisms such as blue stain and mould (Jones and Brischke 2017). Wood-decaying fungi are the most common of the destructive organisms in temperate climates, while termites are a dominant vector in tropical regions.

In this context, and although preservation or modification methods to improve the durability of wood have been developed, some of these processes or chemicals remain expensive, unavailable worldwide, or create potential environmental risks. While research on effective and sustainable

Figure 1.
(a) Tree diversity in the rainforest viewed from the canopy, northern Australia. (b-e) Tree diversity in the rainforest, French Guyana. (c) Wood diversity in test samples form in Laboratory, France. (d) Autoclave for preservative-impregnated wood curing in New Caledonia. (f) Sawmill company in New Caledonia.
Photos © K. Candelier.

Bois et Forêts des Tropiques – ISSN: L-0006-579X
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Figure 2.
(a) Examples of fungal decay test in French laboratory (EN 350-2).
(b) Termite resistance test in French laboratory (EN 118 and EN 117).
(c) Field tests in Queensland - Australia.
Photos © K. Candelier.

preservation and modification methods are still needed, the study of traits related to the natural durability of wood is of great importance for increasing wooden products' service life, choosing an appropriate wood species for an application, and increasing the service life of wooden products in general (Martín and López 2023).

Furthermore, the current context of globalisation and climate change is influencing the biological agents that deteriorate wood materials and wood-based products. On the one hand, globalisation in the trade of wood and wood packaging increases the probability of the inadvertent introduction of forest pathogens and xylophagous microorganisms, which in some cases emerge as invasive species with the potential to attack indigenous forests and timber products. On the other hand, climate change is altering the worldwide distribution of some wood-destroying organisms. Global trade and climate change are inducing a shift in the distribution of invasive organisms (e.g., favouring spreading to higher altitudes) with the potential to cause damage to forest and wood elements, a trend that will probably be exacerbated in the next decades (Brischke and Rapp 2010). There are still important knowledge gaps regarding the mechanisms wood-deteriorating organisms use to attack wood, their ecology and mode of dispersion, and furthermore is some wood traits are affecting the natural durability of wood in service. To improve the social perception of wood as a raw material, further research is needed to develop or improve sustainable methods for preserving wood species of low natural durability against biological deterioration. Finally, it remains important to continue developing durability test methods, experimental studies, and monitoring approaches (figure 2) (Brischke et al. 2023).

Figure 3.
Group picture of the participants at the IRG 54 annual meeting, May 28 - June 1 2023, Cairns, Australia.
Photo © IRGWP.

Focus on the scopes and activities of the International Research Group on Wood Protection (IRGWP)

A brief history

The International Research Group on Wood Protection (IRGWP) (known until 10 June 2004 as The International Research Group on Wood Preservation) was launched as an independent research group in 1969 to continue the work of a previous group of experts on wood protection that had been set up, following an Austrian proposal in 1965, by the Organization for Economic Cooperation and Development (OECD), in Paris, France. In 1979, the Group's administrative Secretariat moved to Sweden and was supported by the Swedish National Board for Technical Development (STU) until 1985. Since then, the IRGWP secretariat remains in Sweden and has been self-financing, relying entirely on the support of its personal and corporate members. Initially, the IRGWP was composed of 22 scientists from nine countries (Austria, Belgium, France, the German Federal Republic, Japan, the Netherlands, Spain, Switzerland, and the United Kingdom). Today, IRGWP has more than 350 members from 51 countries around the world.

Wood protection

The science of wood protection is by nature multi-disciplinary, and can encompass elements of forestry, wood science, mycology, entomology, physics, chemistry, engineering, and technology. Progress in modern wood protection development usually includes two or more of these elements, making the field highly accepting of multi-institutional approaches to solving complex challenges.

Moreover, to adequately describe the current state of wood protection, it requires an approach that involves viewpoints from various regions of the world and, within some of those regions, a country-by-country approach. In this regard, IRGWP has included the following regions of the world: Africa, Asia, Europe, North America, Latin America, and Oceania.

IRGWP's activities

The IRGWP provides the global forum for research and industrial developments in wood protection sciences, including method development, experimental studies, monitoring approaches, models, product development, environmental aspects, etc., in order to promote knowledge about wood durability science and strategies for the protection and preservation of woods, wood-based materials, structures and building components.

Through worldwide cooperation, the IRGWP:

• Facilitates contacts between specialists working on the complex problems of wood protection and durability.
• Issues more than one hundred documents every year, providing members and sponsors with invaluable information.
• Arranges, with the help of local organising committees, annual conferences, and regional meetings with active workshops to discuss and disseminate significant research progress and develop the relationships between academics and industrial companies (figure 3).
• Provides help and encouragement for scientists in developing countries to enable contributions to their research activities and to attend conferences.
• Facilitates the participation of able young scientists in the collaborative research of its Working Parties using the Ron Cockcroft Award scheme[1].
• Works continuously as a forum for discussion and dissemination of research results.
• Avoids duplication of research work and therefore saves time, effort, and money, through its unique around-the-world strategy.
• Shares a durability database aimed at the allocation of wood durability test results (in the field and laboratory conditions) for comparative studies and re-analyses.
• Stimulates progress and quality. IRGWP members and sponsors are proud of their status and strive continuously towards excellence.
• Provides cost-benefits: the annual conferences and the regional meetings provide powerful opportunities for making business contacts while keeping aware of the very latest information in this field.
• Supports financially a permanent Secretariat based in Stockholm, which aims to provide supportive services to members, sponsors, and new interested parties.

[1] https://www.irg-wp.com/RCAGuidelines.html

Bois et Forêts des Tropiques – ISSN: L-0006-579X
Volume 358 – 4th quarter – December 2023 – p. 3-6
EDITORIAL

A brief description of the papers published within this Special issue

This special issue of *Bois et Forêts des Tropiques* was prepared in the framework of the IRG54 annual meeting, which was held in Queensland, Australia, from May 28 to June 1, 2023. During this international meeting, the IRGWP proposed a special session dealing with the natural and conferred durability of tropical wood species. Topics of interest included extractives defense mechanisms against fungi and termites, protection of tropic wood in service (including modification and design), and valorisation of tropical wood with low natural durability.

From these presentations, several papers were selected and are hereby presented in this Special issue. The Scientific Program Committee feels these give a good indication of the current status of durability, preservation and valorisation of tropical wood species, and that you find them as interesting as they did during their presentation during the IRG54 conference.

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A novel wood preservative with plant extracts in a cypermethrin mixture protects envelope-treated tropical kempas hardwood against *Coptotermes* termites when exposed to an above-ground indoor situation after evaporative ageing

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Photo 1.
Two top-covered rectangular zinc containers were positioned upright on the ground at the forest test site for the aboveground termite field test against *Coptotermes curvignathus*. Test wood blocks were held above ground inside the containers in between abundant termite-susceptible baitwood and corrugated cardboard material. Termites invade the contents from below the ground inside the containers.
Photo A. H. H. Wong.

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D. Messaoudi, A. H. H. Wong

RÉSUMÉ

Un nouveau produit de préservation du bois à base d'extraits végétaux mélangés à de la cyperméthrine protège le bois tropical de kempas, traité par imprégnation, contre les termites *Coptotermes*, en situation intérieure, hors-sol, après vieillissement par évaporation

Dans un contexte d'initiatives de l'industrie de la protection du bois visant à développer des solutions de traitement du bois économiquement viables et écologiquement compatibles pouvant remplacer les biocides conventionnels, cet article rend compte d'un essai hors sol de protection contre les dégâts de termites souterrains sur des blocs de duramen de kempas (*Koompassia malaccensis*), un bois dur tropical (malaisien) sensible aux termites. Les blocs ont été traités par imprégnation (brossage) avec un nouveau produit de préservation du bois à base d'extraits de plantes dans un mélange de cyperméthrine (Biocide 1 : 0,16 % de cyperméthrine, 0,08 % de tébuconazole, 2 % d'extraits végétaux). Un traitement disponible à la vente, à base de solvant organique (LOSP) et de perméthrine (Biocide 2 : 0,2 % de perméthrine, 1,8 % de naphténate de tributylétain, 0,1 % de dichlorofluanide) en trempage de 3 mn a servi de traitement de référence. Les blocs de kempas séchés à l'air libre ont subi une fragilisation de type H2 dans le cadre d'un régime rigoureux de volatilisation en laboratoire (représentant un vieillissement long par évaporation du bois traité pour une utilisation hors sol en intérieur dans des situations à risque H2 prolongé). Les blocs ont ensuite été exposés pendant 6 mois en surface, à l'intérieur d'un conteneur d'essai conçu pour les termites souterrains *Coptotermes curvignathus*, sur un site forestier humide (représentant une situation à risque H2 sévère pour bois traité hors contact avec le sol et isolé de l'humidité et des conditions météorologiques). Les résultats ont montré de manière irréfutable que le duramen de kempas non traité était sévèrement attaqué par *C. curvignathus* (perte de masse moyenne : 70,4 % et 20 416 mg), l'indice visuel moyen de présence de termites étant faible (2,4). À l'inverse, le bois de kempas traité était bien protégé avec une très faible rétention en surface du Biocide 1 (perte de masse moyenne négligeable : 0,66 % et 207 mg) et une très faible rétention en surface du Biocide 2 de référence (perte de masse moyenne négligeable : 1,01 % et 306 mg). Les deux traitements ont produit l'indice visuel de présence de termites le plus élevé (10) pour tous les échantillons de kempas répliqués. Les performances des deux biocides sont ainsi semblables, mais diffèrent de manière significative (P < 0,05) de celles des homologues non traités et attaqués. Le biocide 1 a donc un potentiel anti-termites considérable et pourrait remplacer le biocide 2 LOSP conventionnel pour protéger les bois exposés à un environnement à risque H2 à long terme.

Mots-clés : *Coptotermes curvignathus*, pyréthrinoïde, traitement par imprégnation, expérimentation termites, kempas, bois dur tropical, solvant organique, LOSP, additif non-biocide, classe de risque H2, protection du bois.

ABSTRACT

A novel wood preservative with plant extracts in a cypermethrin mixture protects envelope-treated tropical kempas hardwood against *Coptotermes* termites when exposed to an above-ground indoor situation after evaporative ageing

In keeping with sustainability initiatives in the commercial wood protection sector to develop cost-effective, environmentally acceptable wood treatment alternatives to traditional biocides, this paper reports on an above-ground test for protection against subterranean termite damage to blocks of termite-susceptible heartwood of tropical (Malaysian) kempas hardwood (*Koompassia malaccensis*). The blocks were envelope-treated (brush-on) with a novel wood preservative based on plant extracts in a cypermethrin mixture (Biocide 1: 0.16% cypermethrin, 0.08% tebuconazole, 2% vegetal extracts). A commercial permethrin-based LOSP (Biocide 2: 0.2% permethrin, 1.8% tributyltin naphthenate, 0.1% dichlorofluanid) applied in 3-minute dips served as the control treatment. The air-dried kempas blocks were H2-weathered under a rigorous laboratory volatilization regime (representing long-term evaporative ageing of treated wood for above-ground indoor use in prolonged H2-hazard class situations). The blocks were then exposed for 6 months above ground, inside a containerised test design targeting subterranean *Coptotermes curvignathus* termites, at a humid forest site (representing a severe H2-hazard class situation with treated wood isolated from wetting, soil contact, and weather). The results showed irrefutably that untreated kempas heartwood was severely attacked by *C. curvignathus* (mean mass loss: 70.4% and 20,416 mg) with a low mean visual termite rating (2.4). However, the treated kempas wood was well protected at very low surface retention of Biocide 1 (mean negligible mass loss: 0.66% and 207 mg) and very low surface retention of the control Biocide 2 (mean negligible mass loss: 1.01% and 306 mg), with both treatments similarly yielding the highest mean visual termite rating for all replicate kempas specimens (rating 10). The performances of the two biocides were similar but varied significantly (P < 0.05) from the attacks against their untreated counterparts. Biocide 1 therefore has considerable anti-termite potential and could replace conventional LOSP Biocide 2 treatments to protect wood exposed to a long-term H2-hazard class environment.

Keywords: *Coptotermes curvignathus*, pyrethroid, envelope treatment, termite test, kempas, tropical hardwood, LOSP, non-biocidal additive, H2 hazard class, wood protection.

RESUMEN

Un nuevo tratamiento superficial de la madera consistente en una mezcla de extractos de plantas con cipermetrina protege la madera dura de kempas tropical ante las termitas *Coptotermes* cuando se expone a un ambiente interior en superficie después de un envejecimiento evaporativo

Para continuar con iniciativas sostenibles en el sector de la protección de la madera comercial, se desarrollan soluciones de tratamiento de la madera rentables y medioambientalmente aceptables que puedan sustituir a los biocidas tradicionales. Este artículo describe un ensayo de protección en condiciones de superficie contra los daños de termitas subterráneas en bloques de duramen de madera dura de kempas tropical malayo (*Koompassia malaccensis*), vulnerables a las termitas. Los bloques se trataron superficialmente (cepillado) con un nuevo protector de la madera basado en una mezcla de extractos de plantas con cipermetrina (biocida 1: 0,16 % cipermetrina, 0,08 % tebuconazol, 2 % extractos vegetales). Un LOSP (conservante a base de disolventes orgánicos ligeros) comercial basado en el permetrín (biocida 2: 0,2 % permetrín, 1,8 % naftenato de tributilestaño, 0,1 % diclofluanido) aplicado en una inmersión de tres minutos se utilizó como tratamiento control. Los bloques de kempas secados al aire se sometieron a un envejecimiento climático H2 en un riguroso régimen de volatilización de laboratorio (que equivale a un envejecimiento evaporativo a largo plazo de la madera tratada en un ambiente interior sobre una superficie en situaciones de peligro de clase H2 prolongadas). Los bloques se expusieron a continuación durante seis meses en superficie, dentro de contenedores diseñados para ensayos con termitas subterráneas *Coptotermes curvignathus*, en una zona de bosque húmedo (que representa una situación de peligro de clase H2 severa con la madera tratada aislada de la humedad, del contacto con el suelo y de la climatología). Los resultados mostraron irrefutablemente que el duramen de kempas no tratado era gravemente atacado por las *C. curvignathus* (pérdida de masa media: 70,4 % y 20 416 mg) con una valoración visual media de termitas (2,4). Sin embargo, la madera de kempas tratada estaba bien protegida con una retención superficial muy baja del biocida 1 (pérdida de masa media negligible: 0,66 % y 207 mg) y una retención en superficie muy baja del biocida 2 de control (pérdida de masa media negligible: 1,01 % y 306 mg). Ambos tratamientos proporcionaron una clasificación visual media de termitas elevada similar para todas las muestras de kempas replicadas (10). El rendimiento de ambos biocidas fue similar, aunque se diferenció significativamente (P < 0,05) de los equivalentes no tratados atacados. Por lo tanto, el biocida 1 tiene un considerable potencial antitermitas y puede sustituir a los tratamientos convencionales con LOSP biocida 2 para proteger a la madera expuesta a un ambiente con peligro de clase H2 a largo plazo.

Palabras clave: *Coptotermes curvignathus*, piretroide, tratamiento superficial, ensayo con termitas, kempas, madera dura tropical, LOSP, aditivo no biocida, clase de peligro H2, protección de la madera.

Introduction

The wood protection industry in many progressive economies of the world is faced with stringent regulations and environmental pressures and has to develop more environmentally acceptable wood treatment/protection strategies accommodating a fit-for-purpose treatment rationale to protect the wood at low levels of biocide to reduce consequent chemical wastage and environmental contamination normally attributed to excess use of treating solutions. Sustainability and carbon footprint issues are also driving a change in wood preservation, aimed at securing a low-environmental impact wood protection activity at the workplace while securing quality-treated wood products. Traditionally, wood preservation using hazardous heavy metals, creosote, and other organo-metals, either as various forms of water-based solutions, heavy oils or organic solvents that often require high preservative retentions in pressure-treated wood, has raised serious concerns about the workplace safety and environmental safety of such treated wood (UNEP 1994; Freeman et al. 2003). This has spurred wood protection research and development in favour of safer non-arsenical, chromium-free, other non-metallics, organic-based, and bio-based, water-borne wood preservative systems (Barnes 1993; Green III and Schultz 2003; Schultz and Nicholas 2003; Coggins 2008).

Envelope wood treatment technology (using simple dipping, deluging, spray-on or brush-on) with novel formulations has thus emerged and is partly focused on wood protection against termites and decay fungi of solid wood or wood composites. Presumably, these formulations would be superior to traditional emulsifiable concentrates, suspension concentrates, or light organic solvent formulations often using pyrethroid and other organic termiticides at high dosages (Sornnuwat et al. 1994; Peters and Creffield 2003; Donath et al. 2008; Sukartana et al. 2009; Tawi and Wong 2016). Termite testings of these traditional termiticides were also evaluated as pressure-treated wood when increased termiticide penetration into the wood was desired (Creffield et al. 2013; Scown and Creffield 2009). A new generation of bio-based microemulsion termiticidal (pyrethroid-based) formulation technology with KO@LIB antioxidant additive (Messaoudi et al. 2018) has now emerged from the laboratory of Groupe Berkem (France), popular in Europe for envelope (dip) – and pressure-treatment of wood and wood-based products – and has been recently considered in Indonesia using the lowest emission costs (eco-costs) Life Cycle Assessment (LCA) methodology (Siswanti et al. 2016). Also, such enveloped-treated wood from this technology even conferred up to 8 mm cypermethrin penetration into the wood (Ruel et al. 2015). With expertise and knowledge in biocidal formulations, especially for wood preservation, for over 50 years, Groupe Berkem patented the first microemulsion technology for dipping treatments in Europe. Such water-borne products can, with practical dipping or aspersion treatments and adequate dipping times and effective concentrations, also enhance the durability performance of tropical hardwoods against termites under Malaysian H2-H3 biological hazard class conditions (Wong 2004) found in the humid tropics, as was favourably reported in kempas, *Koompassia malaccensis*, dip-treated in a cypermethrin- and a permethrin-based patented microemulsion formulation (Messaoudi et al. 2020ab). The Malaysian biological hazard class selection guide (Wong 2004), broadly similar to that described by the Australian Standards AS1604.1 (AS 2005), classifies H2-hazard class situation where serviced wood such as framing, flooring, and furniture are exposed aboveground indoors and protected from wetting to avoid leaching of biocides from serviced wood (i.e. dry situations), while the test wood samples encountered natural evaporative ageing (i.e. H2-weathering) and termites (and wood borers) under prolonged exposures. H3-hazard class situation concerns wood exposed aboveground outdoors subjected to combined leaching and evaporative ageing (i.e. H3-weathering), termites, wood borers, and decay fungi risks. Pyrethroid-based treated woods are not suitable for use in the more severe, in ground-contact (H4- and H5-hazard class) and marine (H6-hazard class), environments.

Another patented formulation of Groupe Berkem, partly based on a cypermethrin-non-biocidal vegetal extracts mixture (SYNERKEM® technology), is developed as a brushed-on envelope treatment for likely permanent wood protection in aboveground (H2 and H3 hazard class) situations. This paper presents key findings from the accelerated tropical (Malaysian) H2-hazard class subterranean termite test of the performance of this novel bio-based formulation on H2-weathered envelope-treated Malaysian hardwood kempas (*K. malaccensis*) against subterranean termites *Coptotermes curvignathus*.

Experimental methods

The field trials were undertaken using an established H2-hazard class aboveground termite field test protocol (Wong 2005), meant to accelerate termite infestation (and exclude fungal mould growth and decay) and shielded from wetting by rainwater, by exposure of test wood specimens aboveground contact inside covered containers and sandwiched among termite-susceptible wooden baits. Containers were sited on a peripheral humid peat swamp forest area in Kota Samarahan, Sarawak, Malaysia, where subterranean termites *Coptotermes curvignathus* are prevalent (photo 1). *Coptotermes curvignathus* is representative of the aggressive *Coptotermes* subterranean termites found attacking the construction wood of urban buildings in Malaysia and much of Southeast Asia (Lee 2002; Sornnuwat et al. 1996). This termite test protocol (Wong 2005) represents an extreme Malaysian H2-hazard class situation whereby the initially dry situation (no wetting) inside the test assembly ultimately predisposes artificially H2-weathered test wood samples to potential termite risks under prolonged exposures.

The Malaysian hardwood selected for the envelope preservative treatment and termite testing was the structural commercial termite-susceptible kempas (*K. malaccensis*) heartwood material, widely used in Malaysia and abroad for medium to heavy construction indoors and outdoors (Wong 1982; Anonymous 1999). Replicated (n = 8) air-dried test blocks [2.5 × 4 × 5 (length) cm] of kempas (photo 2) heartwood were oven-dried (105 °C, 48 h), weighed, and then allowed to air dry at room temperature for 12 weeks before biocidal treatment. Then, immediately before biocidal treatment, the air-dried blocks were weighed and then dipped for 3 mn, in a reference proprietary nominal 0.2% permethrin-based light organic solvent preservative (LOSP) solution (Biocide 2), and the freshly treated wood was immediately weighed in order to measure weight gain denoting solution uptake (g) meant to estimate surface retention of permethrin expressed as oven dry weight basis (%g/g), wood surface area basis (g/m^2), and wood volume basis (g/m^3) of permethrin. Another replicated (n = 8) set of blocks was brushed-on with the candidate Biocide 1 paste (a cypermethrin-based water-borne preservative mixed with non-biocidal additive vegetal extracts) until the wood surfaces were coated, and then immediately weighed in order to measure weight gain due to coating uptake and hence estimate surface cypermethrin retention similarly as for Biocide 2 treatment. The descriptions of Biocide 1 and Biocide 2 are given in table I. Replicated (n = 8) untreated test blocks served as controls for the experiment. Freshly-treated blocks with Biocides 1 and 2 were then air dried for at least 8 weeks at room temperature to permit the adsorption of pyrethroid in the wood. To simulate the long-term weathered condition of treated wood used aboveground indoors, deemed as H2-hazard class situation (Wong 2004), treated and untreated blocks were next subjected to laboratory evaporative ageing (i.e. Induced H2-weathering) by oven drying at 40 °C for 18 days before termite testing. Such weathered, untreated, and treated wood blocks were exposed to subterranean termites *C. curvignathus* in the field for six months under severe H2-hazard class (i.e. abo-

Photo 2.
Two test blocks {2.5 x 4 x 5 (length) cm] of kempas (*Koompassia malaccensis*) heartwood representing structural medium density hardwoods used in Malaysia.
Photo A. H. H. Wong.

Table I.
Partial composition of candidate Biocide 1 and reference Biocide 2.

Wood preservative product	Nominal composition of active (%g/g)	Solvent	Application
Biocide 1 (Xilix® 7000K)	Cypermethrin (0.16%) Tebuconazole (0.08%) Vegetal extracts (2%)	Water	Brush-on
Biocide 2 (Reference)	Permethrin (0.2%) Tributyltin naphthenate (1.8%) Dichlorofluanid (0.1%)	White spirit	Dipping 3 minutes

Table II.
AWPA E7-07 visual termite rating scale (AWPA 2008).

Rating	Description
10	Sound
9.5	Trace, surface nibbles permitted
9	Slight attack, ≤ 3% of cross-sectional area affected
8	Moderate attack, 3-10% cross-sectional area affected
7	Moderately severe attack and penetration, 10-30% of cross-sectional area affected
6	Severe attack, 30-50% of cross-sectional area affected
4	Very severe attack, 50-75% of cross-sectional area affected
0	Failure (destroyed)

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EXTRAITS VÉGÉTAUX POUR LA PRESERVATION DU BOIS / RECHERCHE

veground contact, protected from wetting) situations inside the termite test assembly of Wong (2005). At the end of the termite field test, the test heartwood blocks were retrieved from the test assembly, cleaned, and visually rated for degree of termite attack (table II, AWPA 2007) using the AWPA E7-07 scale: 10 (sound),..., 6 (severe attack),..., until 0 (failure). The blocks were then re-weighed oven dry (105 °C, 48 h) so as to calculate oven-dry mass differences expressed as percent mass loss per unit before-test oven dry weight, and absolute mass loss (mg).

Data were interrogated by One-way ANOVA using MINITAB-14 software, with multiple comparison t-tests of mean values (for termite rating, percent mass loss, and milligramme mass loss) by Least Significant Difference (LSD, $P < 0.05$) to examine the relative hardwood protection from termites between Biocide 1 treated, Biocide 2 treated and untreated H2-weathered woods blocks.

Results and discussion

Synthetic pyrethroids in both Biocide formulations are of interest here concerning kempas heartwood protection against *C. curvignathus* as fungicides of these biocides are regarded as not effective against termites. The 3-minute dipping of air-dried kempas heartwood with reference Biocide 2 and the brush-on treatment of kempas heartwood with Biocide 1 yielded low mean retentions of each pyrethroid adsorbed onto the wood surfaces (calculated as either g/m^2, g/m^3, or %g/g) shown in table III. Notably, the low applied pyrethroid concentrations in these biocides (0.16% cypermethrin and 0.2% permethrin, table I) were considerably less or quite similar to those normally applied by others in the laboratory (e.g. Read and Berry 1984; Sornnuwat et al. 1994) and field termite tests (Tawi 2019), which expectedly yielded considerably low surface retention expressions shown (table III). Mean Biocide 1 cypermethrin retention in kempas (0.004%g/g, 24.76 g/m^3) differed from that found for kempas dip-treated with 0.16% cypermethrin in microemulsion solution (0.0047%g/g, 40.54 g/m^3) of Messaoudi et al. (2020b). Mean Biocide 2 permethrin retention in kempas (0.0042%g/g, 25 g/m^3) also differed from that in kempas dip-treated with 0.2% permethrin in microemulsion solution (0.0039%g/g, 36.21 g/m^3) of Messaoudi et al. (2020b). It is probable that the microemulsion solutions of Messaoudi et al. (2020ab) can yield slightly higher "g/m^3" retention of these pyrethroids than either Biocide 1 or the reference Biocide 2. Notably, despite the low kempas surface retention of these pyrethroids from Biocide 1 and Biocide 2, both severely H2-weathered treated kempas were nevertheless immune to termite attack compared to H2-weathered untreated kempas, based on mean wood percent mass loss, mean milligramme wood mass loss, and mean visual termite rating values (table IV). There were highly significant differences ($P < 0.05$) in mean termite attacks between treated and untreated kempas [mean termite rating of 10 (for Biocides 1 and 2) versus 2.4 (untreated); mean mass loss of 0.66%g/g (Biocide 1) or 1.01%g/g (Biocide 2) versus 70.4%g/g (untreated); mean absolute mass loss of 207 mg (Biocide 1) or 306 mg (Biocide 2) versus 20,416 mg (untreated)] while comparably excellent performance by Biocide 1 and Biocide 2 was hence confirmed (table IV). However, with pyrethroid formulations, the reference Biocide 2, containing white spirit solvent of LOSP, is increasingly not regarded as environmentally acceptable, unlike alternative pyrethroid biocides such as Biocide 1.

For comparison with previous applications of pyrethroids in traditional formulations, Read and Berry (1984) revealed that a 0.1% concentration of cypermethrin emulsion using surface application was sufficient against *Reticulitermes* termites. Zaidon et al. (2008) found that exposure of rubberwood particleboard, empty fruit bunch (EFB) particleboard, and Rubberwood-EFB particleboard

Table III.
Nominal surface retention of synthetic pyrethroid in wood determined by solution uptake of Biocide 1 (brush-on) and Biocide 2 (dipping).

Wood preservative	Nominal composition of pyrethroid (%g/g)	Mean retention (%g/g)	Mean retention (g/m²)	Mean retention (g/m³)
Biocide 1 (Xilix® 7000K)	Cypermethrin: 0.16	0.0040 (0.0002)	0.14 (0.006)	24.76 (1.05)
Biocide 2 (Reference)	Permethrin: 0.2	0.0042 (0.0004)	0.14 (0.008)	25.00 (1.51)

n = 8; ( ) = standard error of the mean.

Table IV.
Mean values of termite attack parameters comparing 2 treated and 1 untreated kempas, *Koompassia malaccensis*, heartwoods exposed to H2-hazard class situation.

Treatment	Percent mass loss (%g/g)	Absolute mass loss (mg)	Termite rating
Untreated, H2-weathered	70.4 (14.2)	20,416 (4110)	2.4 (1.2)
Biocide 1 (Xilix® 7000K) Surface-treated with cypermethrin/vegetal extracts mixture, H2-weathered	0.66a (0.04)	207a (10)	10a (0)
Biocide 2 Surface-treated with LOSP containing permethrin, H2-weathered	1.01a (0.41)	306a (125)	10a (0)
LSD values	24.21	6984	2.1

LSD values used for comparison within-column mean values: within-column means sharing the same letter "a" denotes that mean values do not differ at $P < 0.05$ sig. level; n = 8; ( ) denotes standard error of the mean.

sprayed with 0.2% permethrin solution yielded low mean mass loss (range: 7.2-12.1%) though failed to confer complete protection, with appreciable attacks on untreated susceptible counterparts (range: 17.8-31.1%) against *C. curvignathus*. Excellent protection was reported from a laboratory evaluation of 5-min dip-treated rubberwood blocks exposed to *C. gestroi* at 0.015, 0.25, and 0.5% cypermethrin and at 0.5, 1 and 2% permethrin (Sornnuwat et al. 1994). Perceivably, such laboratory screening test results, performed without prior evaporative ageing of treated wood blocks, are not necessarily reliable nor comparable with field termite tests, which are realistic for wood protection applications. Indeed, H2-hazard class termite field tests (Tawi 2019) on unweathered wood revealed instead that relatively higher levels of both emulsifiable concentrate-based permethrin (1.69-6.75%) and cypermethrin (1.68-3.35%) agropesticide were needed to fully protect hardwoods from *C. curvignathus* attack. Under similar conditions, traditional water-borne pyrethroid formulations (e.g. emulsifiable or suspension concentrates) could confer termite resistance to dip-treated wood either at longer dipping (steeping) durations, and/or increasing pyrethroid concentrations with consequent termiticide retentions in wood (Sornnuwat et al. 1994; Kamdem et al. 1996; Ma et al. 2013; Tawi 2019). By contrast, when testing weathered treated wood, which represents the true condition of treated wood in longer-term use, Messaoudi et al. (2020b) reported that a 3-minute dipping time protected severely artificially weathered treated kempas remarkably well against termites in the field under H2 and H3 hazard classes, even at their lowest pyrethroid concentrations of microemulsion formulation solution. Termite testing of weathered treated wood represents a realistic measure of longer-term preservative performance against termites in this case, performed also by others (e.g. Peters and Creffield 2003; Sukartana et al. 2009; Creffield et al. 2013). Also, the applied pyrethroid concentrations used with Biocide 1 and microemulsion solutions by Messaoudi et al. (2020ab) were comparably effective to those generally confirmed to be efficient against *Reticulitermes* termites (Adkalis 2018ab).

Since preservative performance against wood-degrading organisms obviously depends mainly on wood species, target preservative retention, treating concentrations and treatment methods, and penetration of the preservative into the wood, the unique envelope treatment microemulsion technology reported by Messaoudi et al. (2020ab) can provide up to 8 mm pyrethroid penetration into wood (Ruel et al. 2015) for termite durability performance in aboveground contact, when adequate wood treatment parameters are applied. There may also be good pyrethroid penetration into kempas shown by the excellent termite resistance performance of Biocide 1 (present study) based on the SYNERKEM® technology, where the component non-biocidal additive vegetal extracts are claimed to act as a booster for cypermethrin efficacy for wood protection and enhancing the fixation of cypermethrin in Biocide 1 into wood cell walls even after evaporative ageing treatment (Ruel et al. 2015). Applying mixtures of non-biocidal additives and organic biocides here represents a novel environmentally friendly concept in wood protection that enhances both the bioefficacy and cost-effectiveness of such a wood preservative system (Green III and Schultz 2003).

Some national wood preservation standards in various regions traditionally specify a high minimum pyrethroid retention with penetration of the active in the wood used in construction, deem as adequately treated wood, and that pyrethroid penetration is achieved via a low-pressure impregnation process. Notably, the Australian Standard AS1604.1 (AS 2005) for preservative treatment of sawn and round timber specifies a relatively higher minimum retention of cypermethrin (0.03%g/g) and permethrin (0.02%g/g) within the 5-8 mm penetration zone, especially for microemulsion or LOSP-based double-vacuum-treated wood for H2-hazard class uses. The exception in AS1604.1 is the use of permethrin, bifenthrin, and imidacloprid for solid wood envelope treatment, albeit at high retention (respectively 0.02%g/g, 0.02%g/g and 0.0078%g/g retention) at the 2 mm penetration zone. However, the present termite test on Biocide 1, as with that of microemulsion-based pyrethroids reported in Messaoudi et al. (2020ab), at considerably lower cypermethrin surface retention (comparable to the reference Biocide 2 LOSP) from envelope treatment, was sufficient to protect kempas against termites as a “fit-for-purpose” wood preservative system. Thus, envelope wood protection of long-lived structures with such innovative formulations (e.g. Messaoudi et al. 2020ab; present study) would certainly befit an environmentally conscious society.

Conclusion

The patented water-borne Biocide 1 formulation (comprising cypermethrin, tebuconazole, and vegetal extracts) provided excellent protection of H2-weathered treated kempas, *Koompassia malaccensis,* from *Coptotermes* subterranean termites aboveground contact indoors exposure, comparable to the reference LOSP Biocide 2 (comprising permethrin, tributyltin naphthenate, and dichlorofluanid), while preliminary observations (to be reaffirmed) even suggest that Biocide 1 could be used to protect wood from termites under H3-weathered situations (treated wood exposed aboveground, outdoors), while the response of the biocide aboveground outdoors to fungal decay threats should also be ascertained. Thus, Biocide 1 is a promising eco-friendly and cost-effective new generation wood preservative for aboveground wood protection against termites, and its use in envelope treatment leads to a greener future for wood protection.

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Access to data
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Natural durability of 8 tropical species suitable for structural roundwood: laboratory screening tests for resistance to fungi and termites

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Photo 1.
(a) Fungal and (b) termite's laboratory screening tests carried out on 8 Guianese wood species.
Photo K. Candelier.

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RÉSUMÉ

Durabilité naturelle de 8 essences tropicales utilisables en bois rond pour la construction : tests rapides en laboratoire de leur résistance aux champignons et aux termites

Les connaissances sur les propriétés des bois tropicaux sont encore relativement limitées, de sorte que leur exploitation se concentre sur quelques essences abondantes et de grand diamètre. Les arbres de petit diamètre sont très peu connus, alors qu'ils pourraient être utilisés directement comme bois rond pour la construction. L'objectif de cette étude est de déterminer la durabilité naturelle de 8 essences potentiellement utilisables en bois rond pour la construction en Guyane française : *Goupia glabra, Licania alba, Hymenopus heteromorphus, Lecythis persistens, Oxandra asbeckii, Pouteria bangii, Simarouba amara, Tachigali melinonii et Virola surinamensis*. Des échantillons de leur bois ont été exposés à la pourriture blanche (européenne et tropicale), à la pourriture brune (européenne) et aux termites souterrains européens (à l'aide de tests sans choix et à choix multiples) dans des conditions de laboratoire, puis soumis à des tests rapides adaptés des normes européennes. Seules deux espèces ont été classées comme durablement résistantes à la fois aux champignons et aux termites : *L. alba* et *P. bangii*, ce qui signifie qu'elles peuvent être utilisées sans traitement comme bois d'œuvre en climat tropical ou tempéré. Les autres essences testées ont été classées (1) durables mais avec des différences notables observées quant à leur résistance aux champignons et aux termites respectivement (*G. glabra, L. persistens, O. asbeckii*), (2) moyennement durables (*H. heteromorphus*), (3) peu durables à sensibles (*T. melinonii, S. amara, V. surinamensis)*, ce qui signifie que les normes européennes actuelles n'autoriseraient pas la mise en œuvre de ces dernières dans des structures extérieures sans protection, malgré leur utilisation par la population locale dans la construction traditionnelle. Cependant, elles pourraient être utilisées pour la construction moyennant des systèmes de protection appropriés (y compris protection du bois). Nos résultats pour la résistance à la pourriture du bois apportent des informations essentielles pour évaluer le potentiel de ces huit essences dans le secteur de la construction en Guyane française.

Mots-clés : Termites, champignons, durabilité naturelle, bois de petit diamètre, bois rond, Guyane française.

ABSTRACT

Natural durability of 8 tropical species suitable for structural roundwood: laboratory screening tests for resistance to fungi and termites

Knowledge of the wood properties of tropical tree species is still relatively limited, so timber extraction focuses on a few abundant, large-diameter species. Very little is known about small-diameter trees, although they could be used directly as roundwood for construction. The aim of this study was to determine the natural durability of 8 candidate species for use as structural roundwood in French Guiana: *Goupia glabra*, *Licania alba*, *Hymenopus heteromorphus*, *Lecythis persistens*, *Oxandra asbeckii*, *Pouteria bangii*, *Simarouba amara*, *Tachigali melinonii* and *Virola surinamensis*. Samples of their wood were exposed to white rot (European and tropical), brown rot (European), and European subterranean termites (using non-choice and multi-choice tests) in laboratory conditions and subjected to screening tests adapted from European standards. Only two species were classified as durable against both fungi and termites: *L. alba* and *P. bangii,* which means they can be used without treatment as building material in tropical or temperate climates. The other species tested were classified (1) as durable but with notable differences observed in their resistance to fungi and termites respectively (*G. glabra, L. persistens, O. asbeckii*), (2) moderately durable (*H. heteromorphus*), (3) low durability to sensitive (*T. melinonii, S. amara, V. surinamensis*), meaning actual European standards would not let use these last species in outdoor structures without protection, despite their use by local population in traditional building. However, they could be used for building purposes with appropriate protection systems (including wood protection). The results we obtained for resistance to wood decay provide essential information to assess the potential of these eight tree species in French Guiana's construction sector.

Keywords: Termites, fungi, natural durability, small-diameter wood, roundwood, French Guiana.

RESUMEN

La durabilidad natural de ocho especies tropicales apropiadas para madera en rollo estructural: pruebas rápidas de cribado de laboratorio sobre la resistencia a hongos y termitas

El conocimiento de las propiedades de la madera de especies de árboles tropicales es todavía relativamente limitado, de manera que la extracción de madera se centra en unas pocas especies abundantes de gran diámetro. Se conoce muy poco sobre árboles de pequeño diámetro, a pesar de que se podrían utilizar directamente como madera en rollo para construcción. El objeto de este estudio era determinar la durabilidad natural de ocho especies candidatas para usar como madera en rollo en la Guayana Francesa: *Goupia glabra*, *Licania alba*, *Hymenopus heteromorphus*, *Lecythis persistens*, *Oxandra asbeckii*, *Pouteria bangii*, *Simarouba amara*, *Tachigali melinonii* y *Virola surinamensis.* Las muestras de sus maderas se expusieron a pudrición blanca (europea y tropical), pudrición parda (europea) y termitas subterráneas europeas (utilizando tests sin selección y con selección múltiple) en condiciones de laboratorio mediante pruebas rápidas de cribado adaptadas según los estándares europeos. Solamente dos especies se clasificaron como resistentes simultáneamente a hongos y termitas: *L. alba* y *P. bangii*, lo que significa que se pueden utilizar sin tratamiento como material de construcción en climas tropicales o templados. Las demás especies ensayadas se clasificaron como (1) duraderas, aunque se observaron diferencias notables en su resistencia a hongos y termitas (*G. glabra, L. persistens, O. asbeckii*); (2) moderadamente duraderas (*H. heteromorphus*); (3) de poco duraderas a delicadas (*T. melinonii, S. amara, V. surinamensis*), lo que significa que los estándares europeos actuales no permitirían que las últimas especies se incluyeran en estructuras exteriores sin protección, a pesar de su uso por la población local en construcciones tradicionales. Sin embargo, podrían utilizarse en construcción con sistemas de protección apropiados (incluyendo tratamientos de la madera). Los resultados que obtuvimos para la resistencia a la descomposición de la madera proporcionan información esencial para evaluar el potencial de estas ocho especies de árboles en el sector de construcción de la Guayana Francesa.

Palabras clave: termitas, hongos, durabilidad natural, madera de pequeño diámetro, madera en rollo, Guayana Francesa.

Introduction

The Guiana Shield is one of the largest continuous areas of lowland tropical rainforest in the world. The forest cover reaches 8 million hectares in French Guiana (1/3 of the French forest) and shelters a unique biodiversity. Forestry operations are, therefore, subject to strict rules, designed to preserve the resilience of the ecosystem, maintain a high level of biodiversity, and ensure the recovery of wood and carbon stocks. It is therefore essential to target the species to be harvested and optimise their processing in order to maximise the added value of the final products. Nowadays, about 90 vernacular timber species (ca. 250 botanical species), out of the 1,800 species of trees inventoried in French Guyana, are considered technologically relevant and therefore of potential commercial value (Guitet et al. 2014). Among this large tree diversity, less than 30 wood species were exploited over the last decades by the local wood industrial chain (Détienne et al. 1989; ITTO 2019). Moreover, 4 timbers (*Louro vermelho*, *Basralocus*, *Mandioqueira* and *Pau roxo*) constitute 75% of the volume harvested (SOMIVAL 2020). Local timber production thus only focuses on a few abundant species (associated with a long renewal period) and values only the old large-sized trees (with a diameter greater than 50 cm). In the context of the growing need for timber, such a production chain can no longer meet the demand while preserving the forest ecosystem. With wood demand expected to triple by 2030 (Houël et al. 2022; SOMIVAL 2020), it is therefore essential to broaden our knowledge about the potentialities of the Guyanese forest resource in order to identify new tree species of interest for timber production.

Small-diameter trees represent an abundant resource in the Amazonian rainforest (Sellan et al. 2023). This resource, unexploited, could constitute an interesting alternative for the construction sector. The most abundant species identified within the diversity of small-diameter trees (from 5 to 10 cm) are slow-growing shade-tolerant species. They produce dense wood (Ramananantoandro et al. 2016; Lehnebach et al. 2019), providing the material interesting mechanical performances suitable for log building, as evidenced by traditional Palikurs constructions (Ogeron et al. 2018). Besides density and mechanics, the choice of the timber in the design of a wooden construction also strongly depends on natural durability, as the intended end-uses (e.g. poles, framings, etc.) do not require the same durability performances (Pilgram 1983). Durability is one of the most important concerns related to the use of timber in construction, whatever the construction system used. Providing more information about this property, as well as other technological characteristics, can help in predicting service life, designing buildings, performance evaluation, and life cycle assessment of wood structures (Brischke et al. 2014). In addition, durability property is a good indicator of the activity of the secondary metabolite constituents and can provide useful leads for wood's valorization through green chemistry applications (Royer et al. 2010; Perrot et al. 2018). To determine the most suitable applications for small-diameter species, it is crucial to address the existing knowledge gap concerning the natural resistance of these woods to biological agents, such as fungi and termites.

Natural durability is an inherent property of wood defined by its resistance to wood-destroying agents. It results from a combination of different parameters like chemical composition (mainly extractives compounds) and anatomical characteristics that are linked to the genetic determinants (Gouveia et al. 2021). The resistance of wood against destroying organisms is complex but can be assessed through a variety of test protocols, whether at a laboratory level or under field conditions (Kutnik et al. 2017). When investigating new species, a first approach may be to evaluate their resistance to specific organisms using reproducible and standardised laboratory-scale tests to allow comparison with more common species already used in construction.

The objective of this research work was to determine the durability of 8 selected Guyanese wood species (table I), with small diameters identified as abundant and undervalued local resources, against European and tropical fungal strains and *Reticulitermes flavipes* termites under laboratory conditions. This property is crucial for discussing the possible uses of these 8-timber species in local log building within the Guyanese construction market.

Material and Methods

Wood Species and Trees Selection

Eight Guyanese tree species were selected because of their rather homogeneous abundance on the whole French Guiana's territory (Jolivot et al. 2008), and their very slender and flawless morphology, answering the objective of providing a low-cost local building material. A ninth wood species was used as a control to test termite and fungal resistance (table I).

The diameter distribution of the selected species, resulting from local inventories[1, 2], is detailed in figure 1. The choice of the species studied results from a combination of different criteria, such as size at maturity, abundance in natural forests, and the potential sylvicultural models of these species. Thus, 5 species were selected: *Hymenopus heteromorphus, Licania alba, Lecythis persistens, Oxandra asbeckii*, and *Pouteria bangii*, whose size at maturity in natural stands does not exceed 30 cm in diameter (with the exception of *L. alba*, i.e. 42 cm), which is the reason why the forestry sector has never been interested in harvesting them. However, for a given geometry, their high wood density suggests good mechanical performance for use as roundwood. These 5 species could complement the

[1] https://paracou.cirad.fr/
[2] https://dataverse.cirad.fr/dataverse/paracou

Table I.
Genus, species, and family names of the selected studied trees, their vernacular names (Molino 2022) in Creole and Bushinengue (Jaouen et al. 2022), and their pilot's name (ATIBT 2016).

Scientific name	Family	Creole name	Bushinengue name	Pilot name (ATIBT)
Goupia glabra Aubl., 1775	Goupiaceae	Goupi, Bois caca	Kopi	Cupiuba
Hymenopus heteromorphus (Benth.) Sothers & Prance, 2016 *var. heteromorphus*	Chrysobalanaceae	Gaulette	Boliken koko	Grigri
Lecythis persistens Sagot, 1885	Lecythidaceae	Mahot rouge	Lebi loabi	Sapucaia
Licania alba (Bernoulli) Cuatrec., 1964	Chrysobalanaceae	Koko, Gaulette	Lebi koko	Grigri
Oxandra asbeckii (Pulle) R.E.Fr., 1931	Annonaceae	n.c.	Muamba	Lancewood
Pouteria bangii (Rusby) T.D.Penn., 1990	Sapotaceae	Balata pomme	Bakuman	n.c.
Simarouba amara Aubl., 1775	Simaroubaceae	Simarouba, Acajou blanc	Asumaripa	Marupa
Tachigali melinonii (Harms) Zarucchi & Herend., 1993	Fabaceae (Caesalpinioideae)	Cèdre Remi	Diaguidia	Tachi
Virola surinamensis (Rol. ex Rottb.) Warb., 1897	Myristicaceae	Yayamadou marecage	n.c.	Virola

n.c.: not communicated.

harvesting of large-sized timber trees in natural forests. *Goupia glabra* was also selected. It is a canopy's species, which consequently reaches a much larger size at maturity, i.e. 62 cm. This long-lived, densely-wooded heliophilic species is already harvested by local logging when mature, but it is also very abundant in small-diameter classes in moderately disturbed forests. It therefore accounts for a substantial proportion of the small-stem volumes resulting from forest clearing and could be valued as roundwood. The last two species selected were *Simarouba amara* and *Tachigali melinonii*. Unlike the others, they have light wood, but their vernacular uses suggest that they could be good candidates for the construction of temporary structures or emergency habitats for which a low-weight material with satisfactory mechanical performance and low resistance to rot is sufficient. In addition,

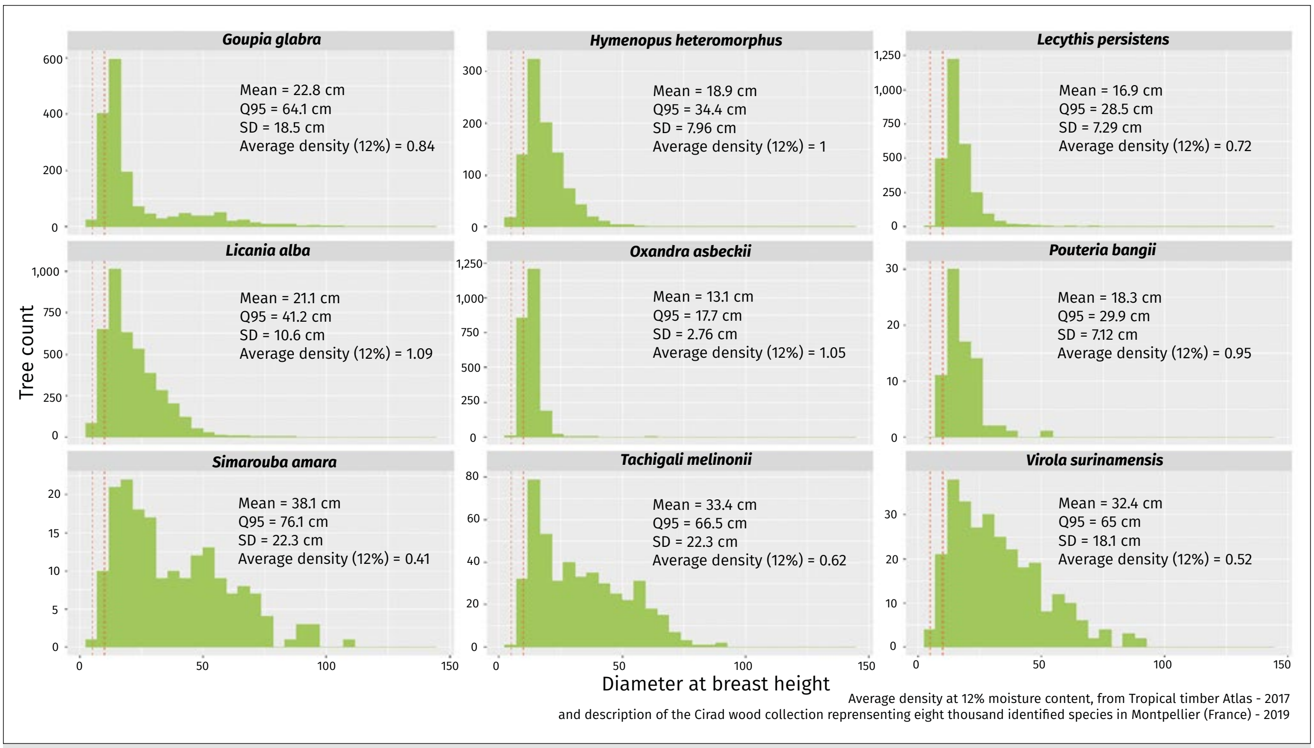

Figure 1.
Distribution of the diameter at breast height of the selected wood species in natural plots. Data are issued from the Guyafor Data Dictionary (https://paracou.cirad.fr/, and https://dataverse.cirad.fr/dataverse/paracou). The values for the average density at 12% are issued from Gerard et al. (2017) and Langbour et al. (2019).

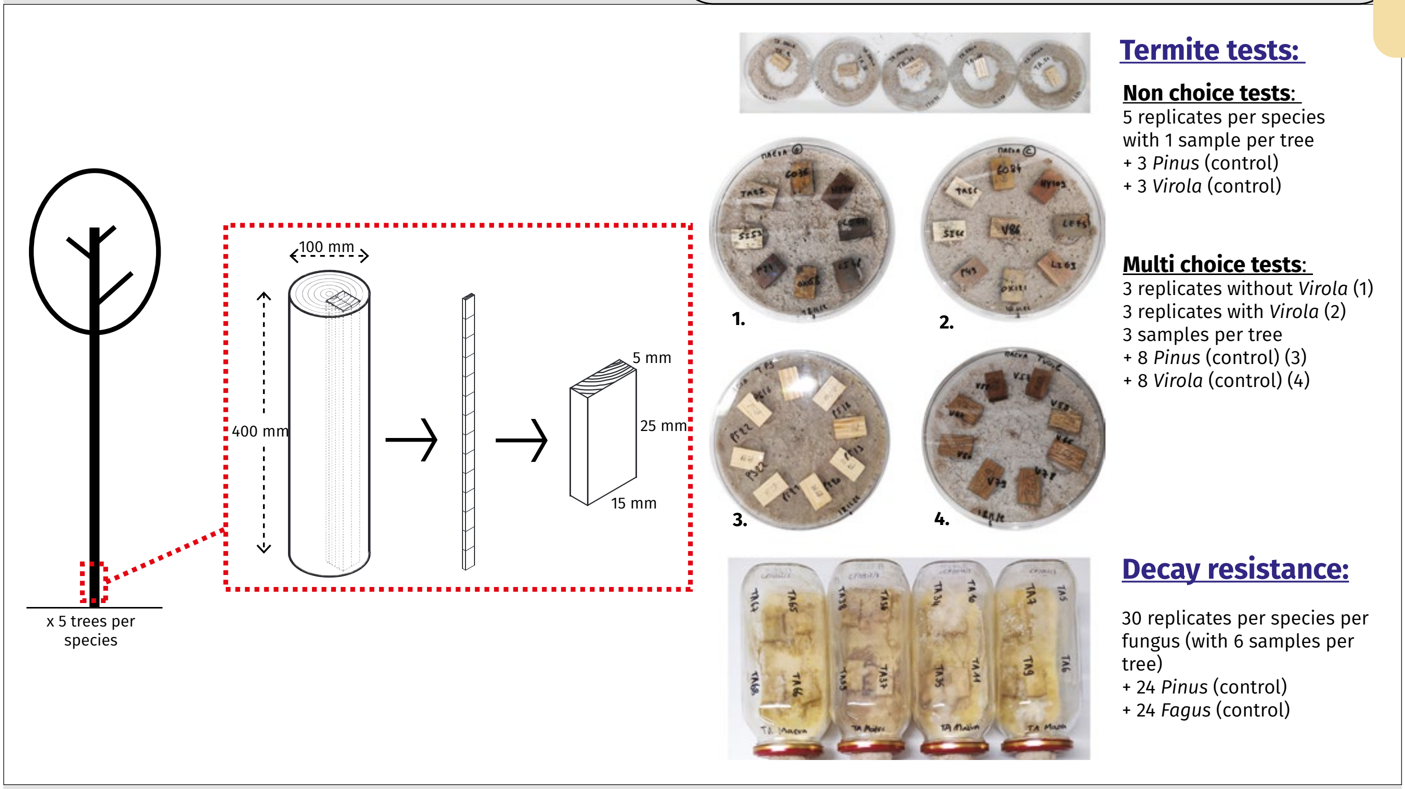

Figure 2.
Sampling plan for each tree and summary of required samples for each experiment (termite or decay tests). Five different trees per species were used to obtain a 40 cm-long stem per tree. 26 samples were cut in each stem, avoiding pith or knots, with dimensions 400 × 15 × 5 mm (L × R × T). Photos M. Leroy.

for example, *S. amara* and *T. melinonii* seem to be rather resistant against insect attack compared to other wood species during sawmill storage. However, their low density is one of the properties that makes their processing (except for the wood with a high content of silica) and implementation relatively easy, as well as their impregnation with anti-fungal and anti-termite bio-treatments. According to Gérard et al. (2017) *S. amara* is classified in treatability class 1 (treatable), whereas *Tachigali* sp. can be classified until treatability class 3 (poorly treatable) according to the genus. It should be noted that *S. amara*, *T. melinonii*, and *G. glabra*, due to their heliophilic temperament and high growth rates, could also be produced as roundwood through short-rotation planting or as a complement to longer-lasting plantations.

For termite and fungal resistance tests, an additional species, *Virola surinamensis*, known for its poor natural durability (Neves et al. 2002), has been added to be tested as a virulence control.

Five trees per species were identified and collected near the Paracou experimental research station[3], in French Guyana (5°16'27''N; 52°55'26''W). This site is a "terra firme" natural forest belonging to the Caesalpiniaceae facies (Sabatier and Prevost 1989), a typical forest type of French Guiana. A total of 45 trees (5 per species) of 6-10 cm diameter were sampled, with the most cylindrical trunks and the longest useful lengths, in order to dedicate the whole tree to other characterization experiments required for round wood uses in building (drying, cracking, mechanical properties, durability field tests, etc.).

Preparation of natural durability tests samples

A 40 cm-long stem portion was collected from the lower part of each selected tree. Several wood pieces longitudinally oriented, 400 × 15 × 5 mm (L × R × T), were sawn from each stem portion. The pieces in the middle of the radial profile were selected in order to maximise heartwood proportion while avoiding the presence of juvenile wood. Finally, pieces were longitudinally cut into 25 × 15 × 5 mm (L × R × T) test samples (figure 2).

To obtain a representative sampling of the exploitable wood, samples exhibiting peculiarities such as knots, slope grain, or reaction wood were discarded (ISO 4471 1982). As the number of samples per tree is limited by the small size of the stem, preference was given to natural durability screening tests (Bravery 1978; Salman et al. 2017), which involve small-sized samples with reduced biological exposure durations, over European standards. In addition, as the objective was to assess the natural durability of the log as a whole, sapwood was not cleared from the samples. From each stem, 26 samples were randomly selected (figure 2): 18 samples to assess the fungal resistance (6 samples per fungus) and 8 samples to assess the termite resistance (5 samples for non-choice tests and 3 samples for choice tests).

[3] https://paracou.cirad.fr/

Resistance against fungal degradation by screening tests

The resistance against wood-destroying rots was tested according to the guidelines of Bravery (1978), i.e. a screening tests adapted from EN 113-2 (2020) for the sample size and the fungal exposure duration.

Glass bottles of 720 ml volume were filled with 65 ml of sterile culture medium [malt extract (40 ± 0.5 g) (Quaron) and agar (20 ± 0.5 g) (Biomérieux) in deionized water (1 l)], inoculated with two small pieces (1 × 1 cm) of a 7-day-old culture mycelium of one brown rot [*Coniophora puteana* (CP) (Schumacher ex Fries) Karsten (BAM Ebw. 15)], one white rot [*Trametes versicolor* (TV) (L.) Lloyd (CTB 863A)], or one white tropical rot [*Pycnoporus sanguineus* (PS) (L.) Murrill, 1904] and then closed with carded cotton to enable air circulation. The inoculated glass bottles were stored for 2 weeks in a climatic chamber regulated at 22 ± 2 °C and 70 ± 5% Relative Humidity (RH) for TV and CP, or 27 ± 2 °C and RH > 75% for PS, until reaching the full colonisation of the medium by the mycelium.

Surface sterilisation of the wood samples before the decay resistance test was performed by ultraviolet radiations (20 minutes per face).

A batch of 10 samples per species was treated separately to calibrate the estimation of the theoretical anhydrous mass of each species tested (m_1). This batch was stabilised (20 ± 2 °C and 65 ± 5 % RH) and weighed (m_s), then oven dried at 103 °C for 48 h and weighed (m_a). The theoretical anhydrous mass (m_1) was calculated using the averaged stabilised mass to oven-dried mass ratio of the batch (k), according to Equation 1 and Equation 2.

$$k=\frac{m_s}{m_a} \qquad (1)$$

$$m_1=k*m_s \qquad (2)$$

The test samples (4 wood samples of the same species per inoculated glass bottle) were incubated for 8 weeks in a climatic chamber (22 ± 2 °C and 70 ± 5% RH for CP and TV; 27 ± 2 °C and RH > 75% for PS). Once the fungal exposure was completed, samples were carefully cleaned. All samples were then oven dried at 103 °C for 48 h and weighed (m_2). The degradation of each sample was assessed by computing the mass loss (ML%) as (Equation 3):

$$ML(\%)=\frac{m_1-m_2}{m_1}\times 100 \qquad (3)$$

Pine sapwood (*Pinus sylvestris*) and beech (*Fagus sylvatica*) samples (12 replicates per fungal strain) were used as virulence controls (pine sapwood for CP and beech for the 3 fungal strains). According to the median ML calculated per species, wood samples were sorted by durability class (table II).

Resistance to termites by screening tests

The Guianese wood species were exposed to subterranean termites (*Reticulitermes flavipes, ex. santonensis*) in non-choice and choice screening tests. Termites were collected from Oleron Island, France (Lat. 45°49'5.9''N; Long. –1°13'47.8''W). The colony was reared in a climatic chamber regulated at 27 ± 2 °C and RH > 75%.

Pinus sylvestris sapwood and *V. surinamensis* samples, with dimensions of 25 × 15 × 5 mm (L × R × T), were also tested against termites as temperate and tropical virulence controls for choice and non-choice tests.

As for the fungal decay tests, both tested and control samples were weighted and their moisture contents measured in order to determine their theoretical anhydrous mass (m_3) before exposure to termites.

Non-choice tests

The non-choice tests were carried out according to the main criteria of the EN 117 (2013), with some adjustments concerning the sample size and the exposure period to the termites. Five replicates (1 sample per tree) and three control samples were tested separately for each species (figure 2). Each specimen was placed on a plastic mesh at the centre of a 9 cm-diameter Petri dish, containing 35 g of Fontainebleau wet sand (4 volumes of sand/1 volume of deionized water). Considering the dimension of the samples to be tested and according to the method used in previous studies (Afzal et al. 2017; Mohareb et al. 2017; Salman et al. 2017; Elaieb et al. 2020), 50 termite workers, one nymph, and one soldier were then introduced into each test device. These test devices were placed for 4 weeks in a dark climatic chamber conditioned at 27 ± 2 °C and RH > 75%. Once a week, water was added and termite behaviour was checked.

At the end of the exposure, the samples were removed, sand was cleaned, and the rate of surviving termites was calculated. Sample degradations were given a visual rating according to the criteria of EN 117 (2013) (the criteria being adjusted to the sample size). Then, the samples were dried at 103 ± 2 °C to obtain their anhydrous mass after termite exposure (m4), and their mass losses (ML%) were calculated similarly to Equation 3.

Table II.
Durability rating scale according to EN 113-2 (2020).

Durability class	Description	Median mass loss (%)
1	Very durable	< 5
2	Durable	> 5 to < 10
3	Moderately durable	> 10 to < 15
4	Slightly durable	> 15 to < 30
5	Not durable	> 30

Multi-choice tests

For the choice tests, 1 sample per species was placed on a plastic mesh around the centre of a 14 cm-diameter Petri dish, containing 150 g of Fontainebleau wet sand (4 volumes of sand/1 volume of deionized water). The 8 Guyanese woods were exposed together to 250 termite workers, 5 nymphs, and 5 soldiers, with and without *V. surinamensis* samples used as controls and placed at the centre of the Petri dish (figure 2). Both modalities were carried out to assess the impact of the presence of a non-durable wood in the multi-choice test devices.

Three replicates of each tested modality were carried out. In addition, two devices containing 8 samples of *P. sylvestris* sapwood or 8 samples of *V. surinamensis* were performed as controls. All the test devices were placed for 4 weeks in a dark climatic chamber conditioned at 27 ± 2 °C and RH > 75%. Termite survival rate, visual rating of wood samples, and mass loss were evaluated just as the non-choice tests.

Results and discussion

Decay resistance

The average values of mass loss on *P. sylvestris* and *F. sylvatica* wood control samples (table III) are respectively above the thresholds required (EN 113-2 2020) hence validating the decay test.

All the results of the decay resistance test are presented in figure 3. For all tested species, a common pattern can be observed: tropical rot (PS) is the most virulent, leading to median mass losses ranging from 4.6% for *P. bangii* to 44% for *V. surinamensis*. In addition, temperate rots virulence appears lower for white rot (TV) than brown rot (CP) considering control species, but this pattern does not apply to all species tested.

Table III.
Median mass loss of *Pinus sylvestris* and *Fagus sylvatica* control samples according to the three tested fungus, and decay resistance validation test conditions relative to EN 113-2 (2020).

	Median Mass Loss (ML) and Standard Deviation In % (m/m)	Minimal (median) mass loss values of control samples, required in EN 113-2 (2020) In % (m/m)
Brown rot on Scots Pine		
Coniophora puteana (CP)	32.0 ± 7.5	30
Brown rot on Beech		
Coniophora puteana (CP)	31.5 ± 6.1	30
White rot on Beech		
Trametes versicolor (TV)	26.2 ± 7.8	20
Optional fungi Tropical White rots on Beech		
Pycnoporus sanguineus (PS)	38.4 ± 3.9	No requirement

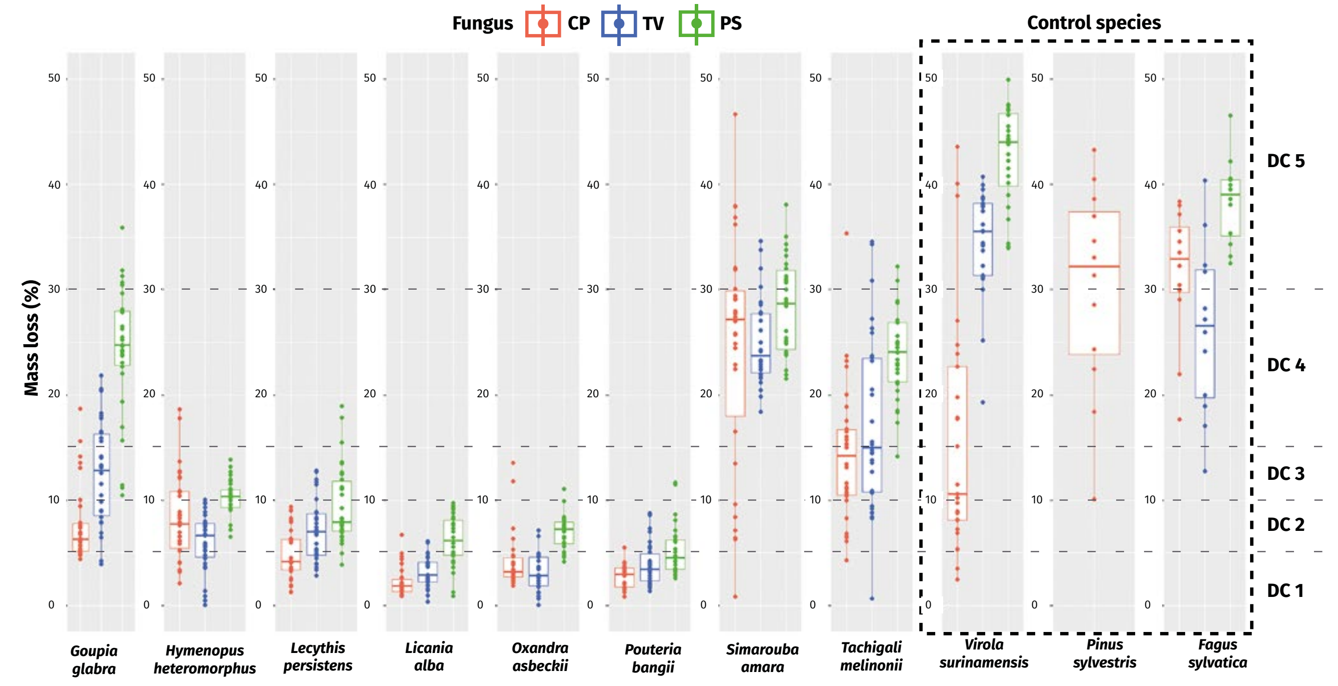

Figure 3.
Mass loss (%) and associated durability class (1 to 5) for all studied species after 8 weeks of exposure to *Coniophora puteana* (CP), *Trametes versicolor* (TV) (temperate rots) and *Pycnoporus sanguineus* (PS) (tropical rot). DC: Durability class.

Goupia glabra, *L. alba*, and *O. asbeckii* median mass losses with tropical rot are about double those of temperate rots. In this sense, it is therefore important to consider the biological risks of the concerned geographical area, by selecting the most discriminant fungal strain that may be encountered in the area where the wood will be used (EN 460 2023). *Lecythis persistens, L. alba, O. asbeckii,* and *P. bangii* present the lowest degradation for all tested rots (table IV).

According to their higher mass loss (ML), recorded with *P. sanguineus*, *P. bangii* (ML = 4.6%) is classified as highly durable (class 1), whereas *L. alba* (ML = 6.2%), *O. asbeckii* (ML = 7.3%), and *L. persistens* (ML = 8.0%) are classified as durable (class 2), meaning they can be used as indoor and outdoor building or joinery materials under tropical climate (within the limits of classes 3 or 4 under certain conditions), without any protection systems. Contrary to *L. alba* and *O. asbeckii*, which have been very little studied, the results obtained for *L. persistens* were expected since the durability of this species has already been studied (Gérard et al. 2017). However, it should be pointed out that this species belongs to a complex gender, gathering many species (with identification difficulties based on simple botanical criteria) having different durability classes [*L. persistens* is class 3 or 4 (Gérard et al. 2017) whereas *L. pisonis* is class 1 or 2 (Comvalius 2001)].

Goupia glabra and *H. heteromorphus* resulted in moderate degradations. Previous studies conducted in Guiana and Suriname also reported *G. glabra* as moderately durable (Van Acker et al. 2000; Chudnoff 1984). Concerning *H. heteromorphus,* no data concerning the wood's natural durability has been found in the scientific literature.

Finally, *S. amara* and *T. melinonii* appeared to be the most degraded species among the rots tested. *Simarouba amara*, as mentioned in the Tropical Atlas Timbers (Gérard et al. 2017), results in susceptible wood species. The Guyanese species tested as a local control, *V. surinamensis,* was classified as susceptible and the most attacked species by the tropical rot (median ML = 44.0%). This result confirms it could be, in that sense, a good marker of rot degradation intensity in a tropical context. However, for temperate rots, and specifically considering only CP results, it appears that *S. amara* (median ML = 28.5%) could be more suitable as a control species than *V. surinamensis* in laboratory conditions (median ML = 18.6%, less than the minimal value of 30% required by the standard) for further decay tests. In other words, particular attention needs to be paid to the choice of the couple (control wood sample; Fungi type) to carry out decay resistance testing on tropical wood species.

The median values of fungal mass losses (ML%) and associated durability classes of the 8-wood species tested after 8 weeks exposure to CP, TV, and PS are detailed in table IV.

Table IV.
Median fungal mass loss (ML%) and associated durability class* (DC, determined from median values according to EN 350 (2016) of the 8-wood species tested), after 8 weeks of exposure to *Coniophora puteana* (CP), *Trametes versicolor* (TV) and *Pycnoporus sanguineus* (PS). *Pinus sylvestris* sapwood, *Fagus sylvatica*, and *Virola surinamensis* have been tested as virulence control samples.

Wood species	Density (20 °C, RH = 65%)	Median value of fugal mass loss (ML) and durability class (DC)* for each tested fungus according to EN 350 (2016)					
		Coniophora puteana (CP)		*Trametes versicolor* (TV)		*Pycnoporus sanguineus* (PS)	
		ML (%)	DC	ML (%)	DC	ML (%)	DC
Goupia glabra	0.888	6.3	2	12.8	3	24.8	4
Hymenopus heteromorphus	1.05	7.7	2	6.6	2	10.4	3
Lecythis persistens	0.869	4.2	1	7.0	2	8.0	2
Licania alba	1.079	1.9	1	2.9	1	6.2	2
Oxandra asbeckii	1.071	3.2	1	2.8	1	7.3	2
Pouteria bangii	1.083	3.0	1	3.4	1	4.6	1
Simarouba amara	0.375	28.5	4	24.1	4	28.7	4
Tachigali melinonii	0.751	14.2	3	15.0	3	24.1	4
Virola surinamensis	0.499	17.7	4	35.5	5	44.0	5
Fagus sylvatica	0.717	32.9	5	26.6	4	39.0	5
Pinus sylvestris sapwood	0.687	33.1	5	n.c		n.c	

* Class 5: Not durable; Class 4: Slightly durable; Class 3: Moderately durable; Class 2: Durable; Class 1: Highly durable.
RH: Relative Humidity

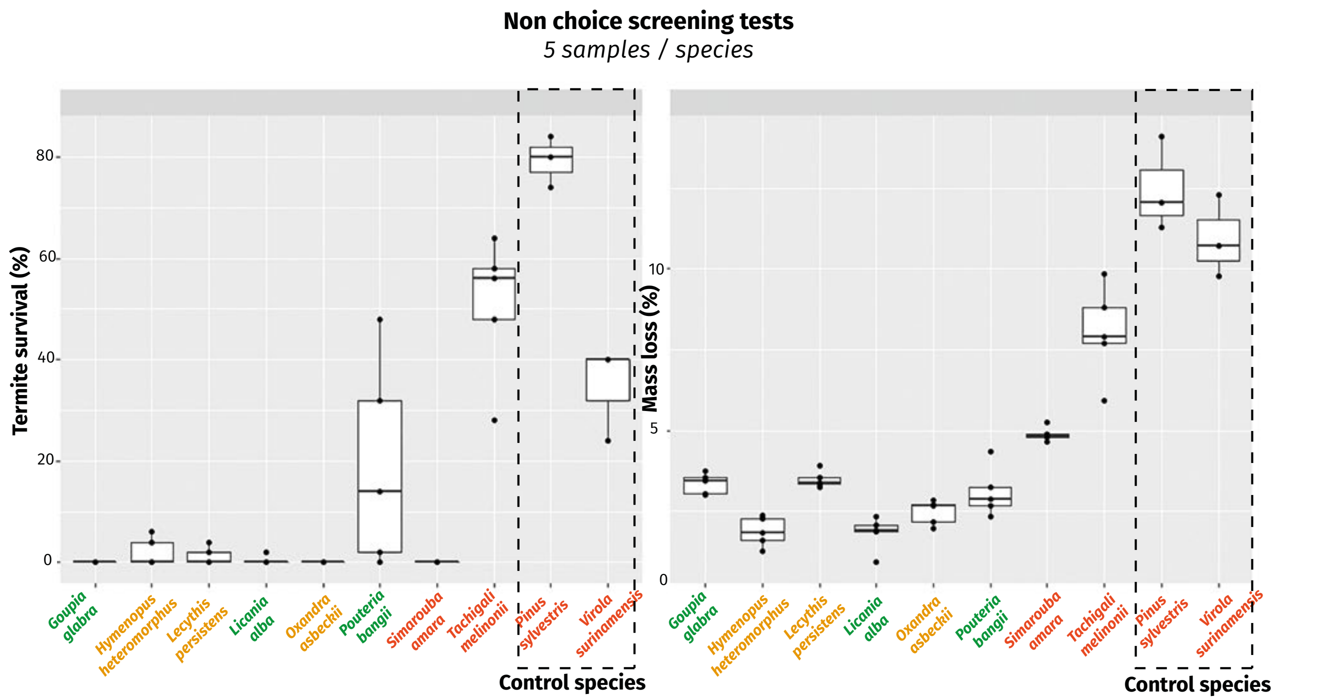

Figure 4.
Termite survival rates (%) and mass loss (%) of the 8 tested species after 4 weeks exposure to *Reticulitermes flavipes* using non-choice tests. *Virola surinamensis* and *Pinus sylvestris* sapwood have been tested as virulence control samples. All the wood species were classified as durable (in green), moderately durable (in orange) or not durable (in red) to termites, according to the visual rating as specified in the EN 350 (2016).

Table V.
Visual rating and corresponding termite durability class determined according to the EN 117 (2013) and EN 350 (2016), of the tested species, after 4 weeks of exposure to *Reticulitermes flavipes* termite using non-choice tests. *Virola surinamensis* and *Pinus sylvestris* sapwood were tested as virulence control samples. Class D: durable, Class M: moderately durable, and Class S: not durable.

Species	Visual rating*	Comments	Durability class EN 350 (2016)
Goupia glabra	1 [5]	more than 90% of the tested specimens are rated 0 or 1	D
Hymenopus heteromorphus	2 [2] - 1 [3]	more than 10% of the tested specimens are rated 2	M
Lecythis persistens	2 [3]- 1 [2]	more than 10% of the tested specimens are rated 2	M
Licania alba	1 [5]	more than 90% of the tested specimens are rated 0 or 1	D
Oxandra asbeckii	2 [2] - 1 [3]	more than 10% of the tested specimens are rated 2	M
Pouteria bangii	1 [5]	more than 90% of the tested specimens are rated 0 or 1	D
Simarouba amara	3 [3] - 2 [2]	more than 50% of the tested specimens are rated 3 or 4	S
Tachigali melinonii	4 [4] - 3 [1]	more than 50% of the tested specimens are rated 3 or 4	S
Virola surinamensis	4 [5]	more than 50% of the tested specimens are rated 3 or 4	S
***Pinus sylvestris* sapwood**	4 [5]	more than 50% of the tested specimens are rated 3 or 4	S

*[X]: number of samples with the respective visual rating.
0: no attack; 1: attempted attack; 2: slight attack; 3: average attack; 4: strong attack.

Resistance towards termites

Non-choice tests

The results from termite resistance non-choice tests carried out on the selected small-diameter round wood species are illustrated in figure 4. The visual rating and corresponding termite durability class according to the standards (EN 117 2013; EN 350 2016) are presented in table V.

The *P. sylvestris* sapwood and *V. surinamensis* control samples were severely degraded (mass loss up to 12.47 ± 1.45% and 10.93 ± 1.26%, respectively, with a termite survival rate of 79.33 ± 5.03% and 34.67 ± 9.24%, respectively). Both sets of control samples have a visual rating of 4 (susceptible to termites). The results from *P. sylvestris* sapwood samples confirmed the high virulence of termites and the validity of the termite resistance tests according to the standards. Interestingly, *V. surinamensis* is also susceptible to termites, but presents a lower termite survival rate than those obtained with *P. sylvestris* sapwood. In this sense, a more appropriate wood species could be used for control samples during termite resistance tests to limit termite mortality and thus better meet the requirements of the standards. It could also be envisaged to raise termites in the laboratory by giving them *V. surinamensis* as their main source of feed, enabling them to adapt their symbiotic system to this wood.

Goupia glabra, L. alba and *P. bangii* appeared to be durable against *R. flavipes*, according to their visual rating of 1 (100% of the five samples tested per species). The mass losses recorded for these three species (< 3.36%) are similar. These results are concordant with previous studies. Comvalius (2001) has determined a similar classification of these three wood species. However, a difference can be observed regarding the termite survival rate (TSR): *P. bangii* seems to be only repellent (TSR = 19.20 ± 20.52%) when *G. glabra* and *L. alba,* appears to be a little more toxic towards termites (TSR = 0.00% and 0.40 ± 0.89%, respectively).

Weekly monitoring of the test devices, giving termite behaviour information, confirms these results.

For *L. alba* samples (figure 5), we observed that all the termites were gathering on top of the wood sample, staying motionless for the whole duration of the test until they all died. According to Haifig et al (2015), "aggregation behaviour is a pattern found among most termites, characterised by high recruitment when a valuable resource is found"; but in the present case, termites were very inactive, hence suggesting that this behaviour was abnormal and unrelated to feeding. Furthermore, most of the individuals were found dead at the end of the experiment. Thus, their aggregation behaviour and death are very probably related to chemical wood compounds that acted as repellents. In addition, most of the wood species from the Chrysobalanaceae family, such as *L. alba* (Wiemann 2010), are known to be very rich in silica, which has high abrasive properties for cutting tools but also for termite mandibles, silica then acts as a digestibility reducer for the enzymatic digestion process of termite (Dhawan et al. 2007).

Pretty similar observations were obtained for *G. glabra*. At the beginning of the test, all termites were attracted by the sample, gathering around it. Finally, they all died during the first week after eating (average ML = 3.5%), proving the toxicity of this species. The anti-termite effect of these wood species could be due to the presence of some toxic or repellent extractive compounds. These properties could be used for the development of natural insecticides for the treatment of non-durable wood species (Rodrigues et al. 2011).

For *P. bangii* and *O. asbeckii*, the two species were less degraded than *G. glabra* (figure 4) and the termites died slightly latter. *Pouteria bangii* and *L. alba,* which here gave interesting resistance to termite attacks, were also the most resistant to rot degradation. Past studies showed that chemical compounds that have been widely isolated from the extractives of *Pouteria* and *Licania* genus included phenolic acid, other phenolics non-flavonoid, flavonoids, and terpenoids derivatives (Fitriansyah et al. 2021; Silva et al. 2012). According to this chemical composition, their extractives might thus be quite effective against both degradation agents (fungi and termites), making them good candidates for log building applications without any treatment.

Hymenopus heteromorphus, *L. persistens* and *O. asbeckii* were classified as moderately durable against *R. flavipes*. They presented a low termite survival rate (< 2.00%), a mass loss under 3.50% (for *L. persistens)* and more than 10% of the tested samples for each wood species presented a visual rating of 2. The *Lecythis* genus gathers several species with sometimes very different properties than those of *L. pisonis* (i.e., *L. idatimon* or *L. persistens* which have low natural durability) (Gérard et al. 2017). Great care must therefore be taken when identifying species within this genus, whose botanical identification is complex.

Finally, *S. amara* and *T. melinonii* showed the highest mass losses among the 8 tested species. Even if their mass losses (*S. amara*: 4.89 ± 0.22%, *T. melinonii*: 8.03 ± 1.46%) were lower than those of both control samples, they were also classified as non-durable towards termite attacks due to their visual ratings (more than 50% of tested samples

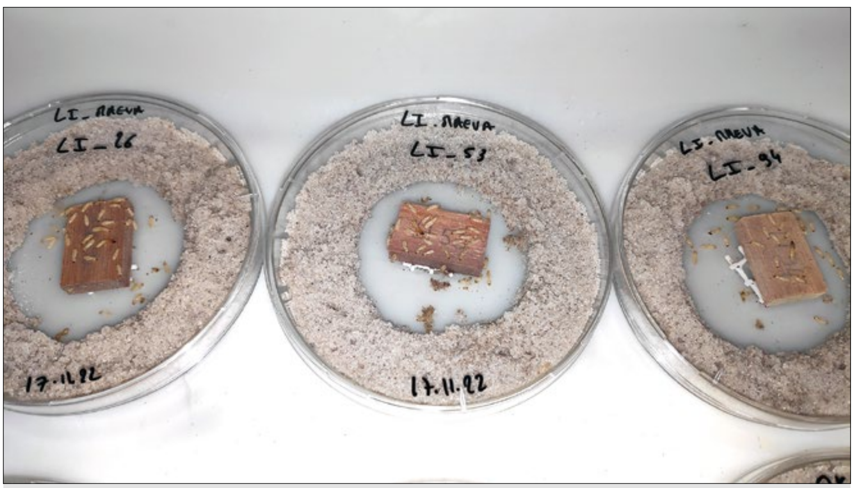

Figure 5.
Licania alba samples in termite resistance using non-choice tests. All the termites were gathering on top of the wood sample, staying motionless, for the whole duration of the test until they all died. Photo M. Leroy.

for each species rated 3 or 4). These findings are consistent with previous studies underlining the sensitivity against termites of *S. amara* and *T. melinonii* (Gérard et al. 2017). Besides, Barbosa et al. (2007) used *S. amara* as a "non-durable" control species and impregnation medium to test the resistance conferred by tropical wood extractives. However, in the same study, the tested samples were exposed to a full colony of *Nasutitermes* sp. for 8 weeks, which probably increased virulence towards the *S. amara* samples used. Still, besides the high level of degradation recorded, it is also worth noting that all termites died after being in contact with *S. amara* (TSR = 0%). It is known that the *Simaroubaceae* family contains quassinoids, secondary metabolites responsible for a wide spectrum of biological activities, including insecticides, antiparasitic, and herbicides (Alves et al. 2014). Finally, regarding *T. melinonii*, the combination of a high degree of degradation and a low impact on termite survival (average TSR = 50.8%, average visual rating = 3 and 4, and average ML = 8,03%), allows us to consider this species as a possible control species with *V. surinamensis* for termite tests.

These results need to be taken with caution. Indeed, the sampling does not really correspond to the one prescribed by the European standards, especially with regard to sample size, orientation, and replicates, resulting from the limitations caused by the specific geometry of the small-diameter sampled round woods. In addition, for these species characterised by non-differentiated wood, even if samples were cut in the middle of the radial profile of each tree, their extractives content and composition remain unknown.

Additional chemical analyses should be done to check that point. However, differences were observed between species, indicating that these results provide a good overview of the natural durability of the selected species if used as roundwood.

Multi-choice tests

The results from termite resistance multi-choice tests carried out on the 8 selected Guyanese small-diameter round wood species are reported in table VI.

The control devices demonstrated a good attractivity (majority of strong attacks recorded through visual rating) and a low termite resistance (*V. surinamensis*: TSR = 14.0%; ML = 8.49 ± 5.56%; *P. sylvestris* sapwood: TSR = 87.6%; ML = 8.1%), validating their use as a control method. For all multi-choice test devices (with and without *V. surinamensis* samples), termite survival was lower than 1.20%. The regular monitoring of test devices carried out during the whole test duration allowed to show that, for both modalities (with and without *V. surinamensis*), the termites were firstly attracted by the *G. glabra* sample.

Figure 6 illustrates the distribution of the mass consumed by the termites according to the wood species and for all test modalities. After one week, termites preferred *L. persistens*, *S. amara*, and *T. melinonii* samples in the absence of the *V. surinamensis* sample. Concerning the test including the *V. surinamensis* sample (figure 6), this one is clearly preferred and attacked by termites compared to the

Table VI.
Average termite's survival rates (%), mass loss (%), and visual rating of the 8 selected Guyanese wood species, after 4 weeks of exposure to *Reticulitermes flavipes* termite species using multi-choice tests (with and without *Virola surinamensis* samples). *Virola surinamensis* and *Pinus sylvestris* sapwood were tested as virulence control samples.

Species	Mass loss (%)	SD (%)	Survival rate (%)	SD (%)	Visual rating*
Termite resistance - Choice test with *Virola surinamensis*					
Goupia glabra	4.46	0.63	0.40	0.69	1 [3]
Hymenopus heteromorphus	1.28	0.46			1 [3]
Lecythis persistens	4.29	0.42			1 [3]
Licania alba	1.71	0.22			1 [3]
Oxandra asbeckii	2.20	0.72			1 [3]
Pouteria bangii	1.91	0.55			1 [3]
Simarouba amara	2.73	0.42			2 [1] - 1 [2]
Tachigali melinonii	2.77	1.13			2 [2] - 1 [1]
Virola surinamensis	27.39	5.26			4 [3]
Termite resistance - Choice test without *Virola surinamensis*					
Species	**Mass loss (%)**	**SD (%)**	**Survival rate (%)**	**SD (%)**	**Visual rating**
Goupia glabra	6.38	0.62	0.00	0.00	1 [3]
Hymenopus heteromorphus	1.81	0.83			1 [3]
Lecythis persistens	5.56	0.78			1 [3]
Licania alba	1.43	0.43			1 [3]
Oxandra asbeckii	2.00	1.05			1 [3]
Pouteria bangii	2.00	0.45			2 [1] - 1 [2]
Simarouba amara	6.61	1.56			4 [1] - 3 [1] -2 [1]
Tachigali melinonii	4.40	0.68			3 [1] - 2 [2]
Control devices					
Species	**Mass loss (%)**	**SD (%)**	**Survival rate (%)**	**SD (%)**	**Visual rating**
Virola surinamensis	8.49	5.56	14.00	0.00	4 [3] - 3 [1]- 2 [2] - 1 [2]
***Pinus sylvestris* sapwood**	8.10	7.02	87.60	0.00	4 [3] - 3 [3]- 3 [2]

*[X]: number of samples with the respective visual rating.
0: no attack; 1: attempted; 2: slight attack; 3: average attack; 4: strong attack; SD: Standard deviation.

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Volume 358 – 4th quarter – December 2023 – p. 15-29

other wood species, even if the *S. amara* and *T. melinonii* samples were also substantially degraded. According to the visual ratings presented in table VI, the most susceptible species to termites in multi-choice tests are *S. amara* and *T. melinonii,* which agrees with the termite durability class determined through the non-choice tests.

Concerning *P. sylvestris* sapwood and *V. surinamensis* control devices in tests (figure 6 in red), the average mass loss (%) after 4 weeks of exposure was 8.49% and 8.10%, respectively (table VI).

Finally, the multi-choice test devices without the *V. surinamensis* sample (in red) have a lower mass loss than multi-choice test devices with the *V. surinamensis* sample (in blue). This result confirms that *V. surinamensis* is an attractive or palatable species for termites and justifies its use as a control species.

The results from the average mass loss (table VI) and the distribution of the mass consumed among the different wood species (figure 6) are consistent with those from the non-choice tests, showing that the less susceptible wood species towards termites are *L. alba*, *H. heteromorphus*, and *P. Bangii*.

Durability classes of all wood species according to the different organisms

Table VII summarises the different durability classes of the 8 tested tropical round wood species concerning their resistance against Basidiomycete fungi (*T. versicolor* and *C. puteana*, *P. sanguineus* tropical strain) and subterranean termites (*R. flavipes*).

Interestingly, *L. alba* and *P. Bangii* demonstrated high natural durability, with the lowest susceptibility towards both fungal and termite attacks. *Goupia glabra* and *O. asbeckii* can be considered as intermediate cases since *G. glabra* is durable considering termite attacks but sensitive to tropical rot, and *O. asbeckii* is highly durable to durable for all rots but sensitive to termites. Something that can still be observed in wooden structures today in French Guiana, such as long-lived *carbets* (wooden shelters without walls, typical of Amerindian cultures), is that the posts sunk into the ground are made of very durable wood species such as *Vouacapoua* spp. or *Minquartia* spp., while the above-ground structure is made of wood species (Annonaceae and Lecythidaceae families) that were slightly less durable (Ogeron et al. 2018). Finally, *H. heteromorphus* and *L. persistens* are moderately durable, while *S. amara* and *T. melinonii* are susceptible to attacks for both tests but evidence toxicity against *R. flavipes* when it is tested in a non-choice test.

However, these results provide an interesting overview of the natural durability of the selected species if used in round wood. To complete these results, it would be interesting to determine and analyse the chemical composition of each tested wood, in order to better identify their defence mechanism and understand the variability of their durability according to the different wood-destroying organisms (Carter and Camargo 1983).

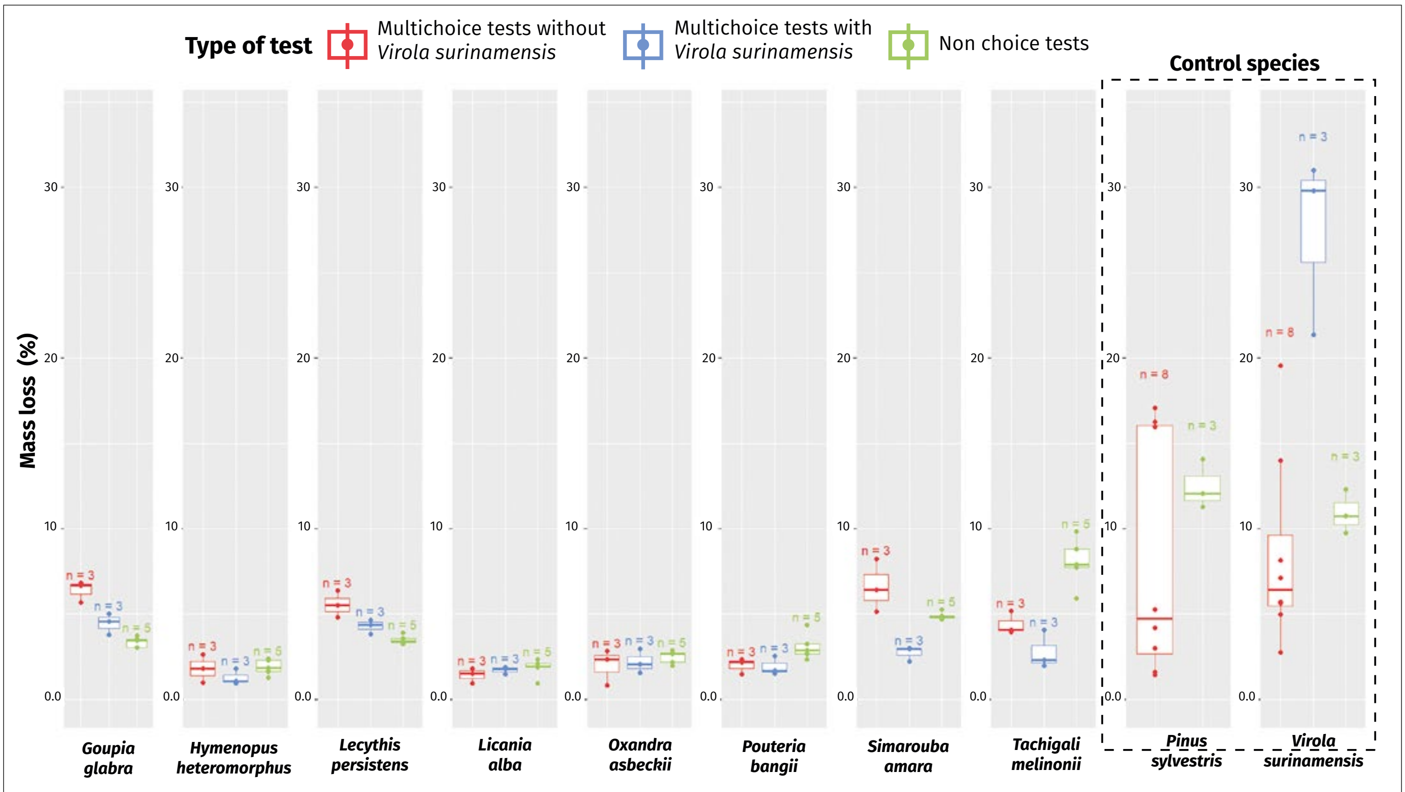

Figure 6.
Mass loss (%) per all studied species after exposure to termites in choice test without *Virola surinamensis* (red), choice test with *V. surinamensis* (blue), and non-choice test (green).

Conclusion

According to fungal and termite tests, only *Pouteria bangii* and *Licania alba* species have sufficient natural durability to be used as building material in ground contact under tropical climate without prior treatment.

Goupia glabra is an interesting species: even though it is poorly durable against fungi, it performed well against termites, showing appetent and termicidal properties.

Oxandra asbeckii and *Lecythis persistens* result as durable against fungi and moderately durable against termites, meaning they need at least a termicidal treatment before any use as building material. Concerning *L. genus*, a high variability in properties could be observed between the different species. In this sense, it is very important to accurately identify the wood species to reach the desired durability level for the final use of wood.

Even if *Simarouba amara* is classified as poorly durable and sensible against termites, a non-choice test indicated that it presents a certain termite toxicity. In this sense, *S. amara* can be used in indoor conditions. In agreement with this statement, it's common to find *S. amara* in the interior floors of old town houses in French Guiana.

Tachigali melinonii results as poorly durable and sensible against termites, *such as Virola surinamensis*, meaning they are not suitable as outdoor wooden material without prior treatment. Regarding treatment, their light microstructure could be one of the properties that would make them more suitable for impregnation, contrary to dense-wooded species such as *O. asbeckii* and *L. persistens*. If no treatment is applied, these light wood species could also be interesting for building light structures or temporary structures for emergency housing, for example.

Ongoing field durability experiments will complement these results, in order to compare the results obtained in controlled conditions at laboratory scale with the performances achievable under real-world conditions of use, where complex phenomena can occur, combining different fungal and termite attacks that can occur concomitantly in a natural environment. This complementary study will allow us to better evaluate and understand the natural durability of these 8 species in round wood in their natural condition. To complete these studies, it would also be interesting to analyse and quantify the chemical compounds present in each species to better understand the defence strategy developed by each species. Such chemical analyses could include a near-infrared spectroscopy survey, allowing further durability classification within each species. The silica content is also an interesting parameter (very variable even at intra-specific scale) that could be measured and linked with termite feeding behaviour.

Finally, the great diversity of Guyanese woods could be better valued, based on sustainable and local uses of a resource to minimise imports and chemical treatments, if more information about their decay resistance was available. In that sense, this study can contribute to the identification of new valorization pathways for the abundant and nonvaluated species tested here. More broadly, diversifying the species used in local constructions would help to limit the exploitation of conventional commercial species and the opening of ever-deeper forest tracks to access to these resources.

Table VII.
Summary of durability classes of the 8 tested round-wood species under laboratory condition using screening tests. *Virola surinamensis*, *Pinus sylvestris* sapwood and *Fagus sylvatica* have been tested as virulence control samples.

Wood species	*Durability classes (EN 350, 2016)*			
	Fungi* [EN 113-2 (2020)]			Termites** [EN 117(2013)]
	Coniophora puteana	*Trametes versicolor*	*Pycnoporus sanguineus*	*Reticulitermes flavipes*
Goupia glabra	2	3	4	D
Hymenopus heteromorphus	2	2	3	M
Lecythis persistens	1	2	2	M
Licania alba	1	1	2	D
Oxandra asbeckii	1	1	2	M
Pouteria bangii	1	1	1	D
Simarouba amara	4	4	4	S
Tachigali melinonii	3	3	4	S
Virola surinamensis	4	5	5	S
Fagus sylvatica	5	4	5	n.c.
***Pinus sylvestris* sapwood**	5	n.c.	n.c.	S

* Class 5: Not durable; Class 4: Slightly durable; Class 3: Moderately durable; Class 2: Durable; Class 1: Highly durable.
** D: Durable; M: Moderately durable; S: Susceptible.
n.c.: not communicated.

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Access to data

The detailed data obtained through this study and presented in this article are available in the "CIRAD Dataverse Portail" with the following reference:
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GNANGUI A., 2022. AGROFORESTRY:
INSTITUTION ET PROTECTION JURIDIQUE DE LA FORÊT ET DES ESPACES BOISÉS EN MILIEU URBAIN.
FRANCE, ÉDITIONS L'HARMATTAN, 166 P.

Les enjeux environnementaux et les conséquences sur la vie humaine de la déforestation préoccupent à juste titre le monde. Cet essai nous montre toutefois que la transposition du patrimoine forestier en milieu urbain est une solution efficiente pour y remédier. L'étude nous montre que, tant en milieu rural qu'urbain, la forêt procure les mêmes bienfaits au plan écologique et climatique. Aussi, en milieu urbain, elle contribue à la régulation des pollutions acoustique et atmosphérique. Il serait désormais nécessaire pour les administrateurs des villes d'intégrer l'institution des forêts dans leur politique de gestion et de disposer de mesures juridiquement contraignantes. Cet ouvrage est accessible à toute personne éprise de qualité de vie urbaine et d'équilibre écologique.

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BOUSQUET F., QUINN T., JANKOWSKI F., MATHEVET R., BARRETEAU O., DHÉNAIN S., 2022. **ATTACHEMENTS ET CHANGEMENT DANS UN MONDE EN TRANSFORMATION.**
FRANCE, ÉDITIONS QUÆ, 126 P.

Posons la question autour de nous : « pourquoi les gens ne changent-ils pas ? ». La réponse sera le plus souvent : « parce qu'ils sont trop attachés à leurs privilèges, traditions, acquis, relations, cultures, terroirs, etc. Ils ne changeront jamais ! ». Cette théorie qui veut que l'attachement empêche le changement fait partie du sens commun. Pourtant, depuis de nombreuses années, les chercheurs qui étudient le concept d'attachement, et notamment l'attachement au lieu, montrent que cette théorie n'est pas validée. L'attachement peut au contraire conférer de la sécurité aux individus et soutenir des changements. Cet ouvrage s'appuie sur des enseignements de la littérature, ainsi que sur des propositions théorique et méthodologique transdisciplinaires. Il est le fruit des interactions entre des chercheurs de différentes disciplines qui ont travaillé en France, au Royaume-Uni, en Afrique du Sud et au Sénégal. La lecture de ce livre invitera, stimulera et guidera les étudiants, chercheurs, décideurs, usagers, ou toutes personnes engagées dans des processus de changement des systèmes sociaux et écologiques dans la prise en compte des attachements et des relations affectives pour accompagner les transitions.

Adapté du résumé de l'éditeur.

Éditions Quæ, c/o INRA RD 10, 78026 Versailles Cedex, France.

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COURBET F., DOUSSAN C., LIMOUSIN J.-M., MARTIN-ST PAUL N., SIMIONI G., 2022. **FORÊTS ET CHANGEMENT CLIMATIQUE : COMPRENDRE ET MODÉLISER LE FONCTIONNEMENT HYDRIQUE DES ARBRES.** FRANCE, ÉDITIONS QUÆ, 2022, 144 P.

Parmi les changements climatiques observés, l'augmentation de la fréquence et de l'intensité des sécheresses est au cœur des préoccupations des forestiers. La rapidité et l'importance de ces changements, la longue durée de vie des arbres, l'impossibilité d'irriguer sont autant de contraintes qui rendent difficile à relever le défi de l'adaptation des forêts. Même si les causes sont multiples, le manque d'eau joue souvent un rôle central dans la détérioration de l'état de santé des arbres. Quel est le fonctionnement hydrique d'un arbre ? Comment réagit-il en cas de sécheresse ? Quels moyens a-t-on d'évaluer sa sensibilité à la sécheresse ? Qu'est-ce qu'un modèle de fonctionnement et à quoi peut-il bien servir ? Cet ouvrage répond à ces questions. Pour faciliter le dialogue entre chercheurs en écophysiologie et utilisateurs des résultats de la recherche, il présente aussi les indicateurs des effets de la sécheresse sur les arbres et les modèles de fonctionnement, avec une fiche descriptive de chaque modèle développé et utilisé par les chercheurs en France. Pédagogique avant tout et abondamment illustrée, cette synthèse nous offre toutes les connaissances pour comprendre, observer et anticiper les effets du changement climatique sur les forêts. C'est l'outil indispensable des étudiants, enseignants, forestiers, chercheurs, acteurs du développement et des politiques publiques.

Adapté du résumé de l'éditeur.

Éditions Quæ, c/o INRA RD 10, 78026 Versailles Cedex, France.

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Comparative decay resistance of plantation-grown and naturally-grown teak wood (*Tectona grandis* L.f.)

Photos 1.
a. A large teak (*Tectona grandis*) tree about 1,500 years old, with a height of 47.8 m, a circumference of 1,007 cm measured on June 18, 2000 before the top of tree was blown up by a storm, is now protected in the Ton Sak Yai National Park, Thailand. b. A row of teak trees along Route 117, Thailand contributes to the maintenance of good landscapes.
c. Plantation teak trees around 20 and 30 years old were harvested and stored in log-yard in Uttaradit Province, Thailand. All photos were taken during a teak expedition organized by Dr. Pipat Pattanaponpaiboon and Dr. Sasitorn Poungparn (Plant Ecology Laboratory), Faculty of Science, Chulalongkorn University in July 2023.
Photos K. Yamamoto.

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K. Yamamoto

RÉSUMÉ

Comparaison de la résistance à la pourriture du bois de teck de plantation et du bois de teck naturel (*Tectona grandis* L.f.)

Le teck (*Tectona grandis* L.f.) est une des essences tropicales les plus largement utilisées en raison de sa durabilité naturelle. L'aubier, le duramen externe, moyen et interne et la moelle du teck de plantation (Indonésie) et du teck naturel (Myanmar) ont été testés pour leur résistance à la pourriture (composante majeure de la durabilité naturelle des bois), en appliquant un test de pourriture accélérée conformément à la norme JIS Z 2101 (1994) en présence de pourriture blanche (*Trametes versicolor*) et de pourriture brune (*Fomitopsis palustris*). Des blocs de bois de 20 × 20 × 10 mm ont été découpés dans des disques prélevés sur le rayon de la tige. Le pourcentage de perte de masse dû à la pourriture dans chaque bloc a été obtenu après 12 semaines d'incubation avec ces champignons. Les pertes de masse moyennes dues à *T. versicolor* sont les suivantes pour, respectivement, le teck de plantation, le teck naturel (n° 1) et le teck naturel (n° 2) : aubier 21,4 %, 7,1 % et « absence de données » ; duramen extérieur 0,6 %, 3,6 %, 6,6 % ; duramen moyen 2,3 %, 6,5 %, 5,7 % ; duramen intérieur 10,3 %, 9,6 %, 6,0 % ; moelle 13,0 %, 15,3 %, 8,2 %. Les pertes de masse dues à *F. palustris* sont, respectivement : aubier 7,5 %, 3,0 %, 7,5 % ; duramen externe 0,0 %, 2,5 %, 2,7 % ; duramen moyen 0,0 %, 2,2 %, 2,3 % ; duramen interne 4,9 %, 2,0 %, 3,4 % ; moelle 13,6 %, 8,4 %, 8,0 %. La durabilité a été classée en référence à Osborne (1970), en se basant sur le pourcentage moyen de perte de masse du duramen due à la pourriture fongique. Dans l'ensemble, parmi les échantillons de teck de plantation et de teck naturel, seuls les duramen externe et moyen étaient durables. La durabilité pour le duramen interne est modérée, mais faible pour la moelle. Aucune différence nette de résistance à la pourriture n'a été constatée entre le teck de plantation et le teck naturel.

Mots-clés : *Tectona grandis*, duramen, durabilité naturelle, résistance aux champignons lignivores, provenance, bois de teck, plantation tropicale, Indonésie, Myanmar.

ABSTRACT

Comparative decay resistance of plantation-grown and naturally-grown teak wood (*Tectona grandis* L.f.)

Teak (*Tectona grandis* L.f.) is one of the most popular tropical timber species for its natural durability. The sapwood, the outer, middle, and inner heartwood, and the pith of plantation-grown teak in Indonesia and naturally grown teak in Myanmar were tested for decay resistance (a major component of natural durability), applying an accelerated decay test according to JIS Z 2101 (1994), and using a white rot fungus (*Trametes versicolor*) and a brown rot fungus (*Fomitopsis palustris*). Wood blocks 20 × 20 × 10 mm in size were cut from discs across the radius of the stem. The percentage mass loss in each block caused by decay was obtained after 12 weeks of incubation with these fungi. Mean mass losses due to *T. versicolor* were respectively as follows for plantation-grown, naturally-grown (No. 1), and naturally-grown (No. 2) teak: sapwood 21.4%, 7.1%, "no data"; outer heartwood 0.6%, 3.6%, 6.6%; middle heartwood 2.3%, 6.5%, 5.7%; inner heartwood 10.3%, 9.6%, 6.0%; pith 13.0%, 15.3%, 8.2%. Mass losses due to *F. palustris* were, respectively: sapwood 7.5%, 3.0%, 7.5%; outer heartwood 0.0%, 2.5%, 2.7%; middle heartwood 0.0%, 2.2%, 2.3%; inner heartwood 4.9%, 2.0%, 3.4%; pith 13.6%, 8.4%, 8.0%. Durability was classified with reference to Osborne (1970), based on the mean percentage mass loss of heartwood caused by fungal decay. Only the outer and middle heartwood were generally durable in both plantation-grown and naturally grown teak specimens. The inner heartwood was moderately durable, but pith durability was low. No clear differences in decay resistance were found between plantation-grown and naturally-grown teak.

Keywords: *Tectona grandis*, heartwood, natural durability, decay resistance, provenance, teakwood, tropical plantation, Indonesia, Myanmar.

RESUMEN

Comparación de la resistencia a la descomposición de la madera de teca (*Tectona grandis* L.f.) de plantación y de crecimiento natural

La teca (*Tectona grandis* L.f.) es una de las especies de madera tropical más populares por su durabilidad natural. Se ensayó la resistencia a la descomposición (una componente importante de la durabilidad natural) de la albura, el duramen exterior, intermedio e interior y la médula de la teca de plantación de Indonesia y de la teca crecida naturalmente en Myanmar. Para ello se realizó un ensayo de descomposición acelerada según JIS Z 2101 (1994) utilizando un hongo de pudrición blanca (*Trametes versicolor*) y un hongo de pudrición parda (*Fomitopsis palustris*). Los bloques de madera de talla 20x20x10 mm se cortaron de discos a lo largo del radio del tronco. El porcentaje de pérdida de masa causada por la descomposición en cada bloque se obtuvo después de doce semanas de incubación con estos hongos. Las pérdidas de masa medias debidas a *T. versicolor* fueron respectivamente las siguientes para teca crecida en plantación, crecida naturalmente (nº 1), y crecida naturalmente (nº 2): albura 21,4 %, 7,1 %, "sin datos"; duramen exterior 0,6 %, 3,6 %, 6,6 %; duramen intermedio 2,3 %, 6,5 %, 5,7 %; duramen interno 10,3 %, 9,6 %, 6,0 %; médula 13,0 %, 15,3 %, 8,2 %. Las pérdidas de masa debidas a *F. palustris* fueron, respectivamente: albura 7,5 %, 3,0 %, 7,5 %; duramen exterior 0,0 %, 2,5 %, 2,7 %; duramen intermedio 0,0 %, 2,2 %, 2,3 %; duramen interno 4,9 %, 2,0 %, 3,4 %; médula 13,6 %, 8,4 %, 8,0 %. La durabilidad fue clasificada en referencia a Osborne (1970), según el porcentaje medio de pérdida de peso del duramen causada por descomposición fúngica. Solamente el duramen externo e intermedio eran generalmente duraderos tanto en ejemplares de teca provenientes de plantación como en ejemplares de teca de crecimiento natural. El duramen interno era moderadamente duradero, pero la durabilidad de la médula era baja. No se encontraron diferencias claras entre la resistencia a la descomposición de la teca proveniente de plantación o crecida naturalmente.

Palabras clave: *Tectona grandis*, duramen, durabilidad natural, resistencia a la descomposición, procedencia, madera de teca, plantación tropical, Indonesia, Myanmar.

Introduction

From the perspective of global warming countermeasures such as represented by the Sustainable Development Goals (SDGs), it is essential to curb the use of fossil resources and promote the better utilisation of natural resources, especially forest resources. It has been noted that wood-based products, as a representative of bio-based materials, should play an important role in the substitution of fossil resources to produce energy, fibre, and other manufactured goods (Verkerk et al. 2022). A prediction of the doubling of global resource use by 2050 would likely outstrip global sustainable supply and trigger negative impacts on biodiversity, climate, ecosystems, and human wellbeing (ITTO 2021). Wood resources are expected to play a leading role in the substitution of non-renewables because the increasing demand for goods in the construction sector and other sectors like plastics and textiles can partially be met by wood-based products (Held et al. 2021), though the carbon costs of 3.5-4.2 Gt CO_2e/year have been estimated as the increasing global wood harvests between 2010 and 2050 (Peng et al. 2023).

Tropical timbers have long been supplied to the rest of the world by timber-producing countries, but their supplies have significantly declined over the years because of unabated deforestation, forest alteration, and human settlement (Giam 2017). It is also mentioned that the boom-and-bust export pattern of tropical timber trade is rooted in tropical countries' own policies and unsustained-yield forestry (Vincent 1992). Demands for wood resources from plantation forests for the replacement of natural forest resources are steadily increasing in these years. It was predicted that increases in demand for paper products and construction-related materials would indicate fast-growing wood plantations playing a larger role in the future wood market (Elias and Boucher 2014). According to "The State of the World's Forests 2022" by FAO (2022), planted forests cover 294 million ha (7 percent of the global forest area), with the area increasing by a rate of just under 1 percent per year in 2015-2020, down from 1.4 percent per year in 2010-2015. There are many concerns about the environmental effects on plantations, particularly large-scale ones (Sawyer 1993). Although these timber plantations may have negative implications for biodiversity, ecosystem services, and local communities, integrated policies that strike a balance between reducing environmental impact and the necessity for forest products will maximise the potential benefit of both plantations and natural forests (Pirard et al. 2016).

The production of trees characterised by a higher growth rate, higher natural durability, and lower lignin content, among others, are important technological methods to contribute to the increasing demand for wood. The spread of wood species with high natural durability increases the value of timber products and also contributes to the SDGs thanks to the longer service life of the products (United Nations 2017). Fortunately, much research on the durability of wood, especially in tropics, has been carried out not only in producer countries (Foxworthy 1930; Eddowes 1977; Hong and Yamamoto 1990), but also in timber-importing countries (Chudnoff 1984; Timber Research and Development Association 1979; Gérard et al. 2017; Matsuoka 1970).

Teak (*Tectona grandis* L. f.) is one of the most popular tropical timber species in relation to its natural durability against decay fungi and especially termites on land. Because of its high value, the development of fast-growing teak plantations continues to expand in the tropics, and the planted teak area has increased significantly in Africa, Central America, and South America since 1995 (Kollert and Kleine 2017). The high natural durability of teak heartwood against wood-destroying fungi and termites is confirmed by many authors (Rudman et al. 1967; Bhat 1998; Thulasidas and Baillères 2017). Especially, there is great interest in the durability of short-rotation teak. Some studies showed fast-growing teak was not necessarily inferior in natural durability (Trockenbrodt and Josue 1999; Rodríguez-Anda et al. 2019; Martha et al. 2022), while others mentioned it was generally less durable than mature teak (Bhat et al. 2005; Thulasidas and Baillères 2017). Somewhat inconsistent results are attributed to the wide radial variation of natural durability (Da Costa et al. 1961), proportion of juvenile wood in heartwood (Bhat et al. 2001), and considerable variations of durability among provenances (Kokutse et al. 2016; Niamke et al. 2018). The content of extractives related to heartwood formation was also examined in plantation-grown and naturally-grown teak wood. The age of trees did not significantly influence the extractive concentration among 9, 15, 21 years old plantation-grown teak in Mexico (Rodríguez-Anda et al. 2019). In contrast, extractive contents, especially tectoquinone, were significantly higher in 100 years old naturally-grown teak from Myanmar than in 29 years plantation-grown teak from Panama (Haupt et al. 2003). A recent review of teak research presents the following key findings on natural durability (Thulasidas and Baillères 2017): (i) wood from fast-growing plantations is often less durable (Gérard et al. 2017), (ii) durability increases from the pith to the outer heartwood, and is largely determined by the various polyphenolic compounds especially particular individual chemicals, (iii) juvenile wood found near the pith offers less durability and teak does not reach maturity until 20-25 years of age, and (iv) it is advisable to retain teak trees for 60 years or more, disregarding the short-term investments and benefits on some occasions. Thulasidas & Baillères (2017) concluded that the key to growing teak is to improve the properties of the immature heartwood.

This paper aims to assess the difference in decay resistance between plantation-grown from Indonesia and naturally-grown teak from Myanmar. In addition, the comparative analysis of the fungal mass loss has been carried out across the radial transect (pith-to-sapwood) of tree stems in order to better understand the difference between plantation-grown and naturally-grown teak durability properties.

Materials and Methods

A total of three discs of *Tectona grandis* wood with around 4 cm in thickness were obtained from a plantation forest in KPH Banyumas Barat, Central Jawa, Indonesia, and from a natural forest in Myanmar through the HOXAN CORPORATION, Japan in 1998 (table I). Sole plantation teak disc was 36 cm in diameter with 18 growth rings. One natural teak disc (No. 1) was 58 cm in diameter with 106 growth rings, and the other one (No. 2) was 64 cm in diameter with 245 growth rings. The heartwood percentage of sample discs was 69, 87, 88%, respectively. The height of the trunk at which these sample discs were obtained was not identified. Sample discs were grouped into nine radial parts from sapwood to the opposite sapwood across the radius of the stem via pith (figure 1). Heartwood was divided into three equal widths, except the pith. The nine parts consist of two sapwoods, two outer heartwoods, two middle heartwoods, two inner heartwoods, and one pith. Six wood block specimens of 20 × 20 × 10 (longitudinal) mm in size were cut from each part except sapwood of natural teak discs. The sapwood of natural teak discs almost disappeared, probably during the transportation of logs, only two specimens could be obtained from the inner part of the sapwood (intermediate wood) of each disc. Therefore, the data for the sapwood of natural teak discs were used as references. Each of three replicate wood specimens was subjected to the accelerated laboratory decay test by the white rot fungus *Trametes versicolor* and the brown rot fungus *Fomitopsis palustris*, respectively, according to JIS Z 2101 (1994) (figure 1).

Table I.
Characteristics of sampled discs and replicate numbers of the fungal test.

Sample discs	Number of trees and discs		Diameter and number of growth rings of the disc		Replicate number of specimens for each fungus	Origin****
	Trees	Discs	Diameter (cm)	Growth rings		
Plantation	1	1	36	18	3*	Central Jawa, Indonesia
Natural (No. 1)	1	1	58	106	3**	Myanmar
Natural (No. 2)	1	1	64	245	3***	Myanmar

* Three replications of each part for *Trametes versicolor* and *Fomitopsis palustris*.
** Three replications, except one replication of sapwood block for both fungi and one for the pith for *T. versicolor*.
*** Three replications, except one replication of sapwood block for both fungi.
**** Provenance from plantation- and natural trees is different. Landraces of Indonesian plantation teak trees showed a mixed pattern of various origins based on genetic diversity (Hansen et al. 2017)

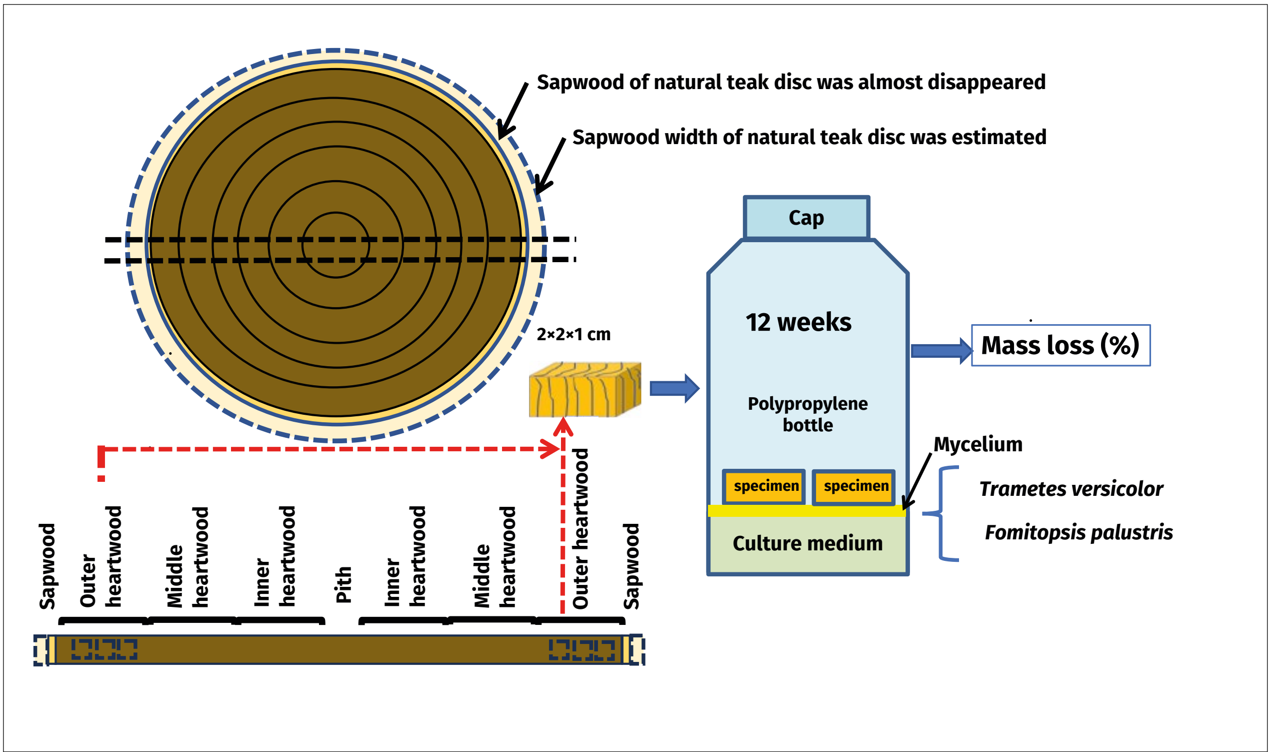

Figure 1.
Schematic diagram of wood specimen preparation and fungal decay test. Wood specimens were prepared across the radius of the stem via pith, and heartwood was divided into three equal widths except the pith (4 cm width).

Table II.
Mass losses of teak wood, *Tectona grandis* L.f., decayed by *Trametes versicolor* and *Fomitopsis palustris*.

Sample	Position	Mass loss (%) by *Trametes versicolor* (standard deviation)	Mass loss (%) by *Fomitopsis palustris* (standard deviation)
Plantation teak, *Tectona grandis* L.f.,	Sapwood	21.4 (3.2)	7.5 (7.3)
	Outer heartwood	0.6 (0.5)	0.0 (0.0)
	Middle heartwood	2.3 (2.0)	0.0 (0.0)
	Inner heartwood	10.3 (5.8)	4.9 (3.5)
	Pith	13.0 (4.3)	13.6 (9.3)
Natural teak (No. 1)	Sapwood***	7.1 (-)*	3.0 (-)*
	Outer heartwood	3.6 (1.8)	2.5 (1.2)
	Middle heartwood	6.5 (3.6)	2.2 (1.0)
	Inner heartwood	9.6 (3.1)	2.0 (2.8)
	Pith	15.3 (-)*	8.4 (1.4)
Natural teak (No. 2)	Sapwood***	**	7.5 (-)*
	Outer heartwood	6.6 (2.7)	2.7 (0.7)
	Middle heartwood	5.7 (1.9)	2.3 (2.3)
	Inner heartwood	6.0 (1.1)	3.4 (4.9)
	Pith	8.2 (4.3)	8.0 (5.2)
Reference: *Fagus crenata*	Sapwood	53.7	37.4

Number of replicate specimens was three unless otherwise noted.
* Replicate specimen was one. ** Test specimen was contaminated during the decay test, and the mass loss could not be determined efficiently. *** Data of sapwood of natural teak (No.1 and 2) were used as references because of the limitation of sample number and quality.

The percentage of mass loss in each specimen caused by decay was obtained after 12 weeks of incubation with these fungi. The reference wood species was the sapwood of *Fagus crenata* for hardwood and the sapwood of *Cryptomeria japonica* for softwood in the JIS. The mean mass loss of *F. crenata* was 53.7% by *T. versicolor* and 37.4% by *F. palustris*.

Classes of natural durability are usually determined by the mass loss ratios of test specimens to reference ones in EN 350 (2016), or by the mass loss values of test specimens in ASTM D 2017-05 (2005). When the EN or ASTM criteria were used as a reference, for instance, sapwood was classified as moderately durable or resistant in this study because the mean mass losses of teak wood, both sapwood and heartwood, were quite low compared with the mass loss of the reference species *F. crenata* sapwood (table II). Therefore, the durability class rating based on the mass losses measured by the laboratory decay test by Osborne (1970) for tropical rainforest timbers was referred to in this study. This rating adopted 4 classes: “durable” (less than 3% mean mass loss), “moderately durable” (3-10%), “slightly durable” (10-20%), and “nondurable” (more than 20%).

Result

The mean mass losses (%) of test specimens caused by *T. versicolor* and *F. palustris* are presented in table II. Mean mass losses of sapwood by *T. versicolor* were 21.4% in plantation wood, 7.1% in natural wood (No. 1), and no data (contaminations had occurred in the test device during the decay experiments) in natural wood (No. 2). Those of outer heartwood were 0.6%, 3.6%, 6.6%, middle heartwood were 2.3%, 6.5%, 5.7%, inner heartwood were 10.3%, 9.6%, 6.0%, and pith were 13.0%, 15.3%, 8.2%, respectively. Mean mass losses of sapwood by *F. palustris* were 7.5% in plantation wood, 3.0% in natural wood (No. 1), and 7.5% in natural wood (No. 2). Those of outer heartwood were 0.0%, 2.5%, 2.7%, middle heartwood were 0.0%, 2.2%, 2.3%, inner heartwood were 4.9%, 2.0%, 3.4%, and pith were 13.6%, 8.4%, 8.0%, respectively. These laboratory decay tests are comparative among the radial positions of heartwood and sapwood, between plantation wood and natural wood. The following results are obvious: (i) the outer and middle heartwood were more decay resistant than the inner heartwood for both in plantation wood and natural wood; (ii) the inner heartwood (juvenile wood), including the pith was less decay resistant both in plantation wood and natural wood; and (iii) there seem to be no distinctive differences in decay resistance between plantation wood and natural wood.

Discussion

Though the results of this preliminary study were based on a small quantity of tested samples and insufficient information on the origin of specimens, the following discussions about the classification of natural durability, proportion of heartwood, and variation of decay durability across the radius of the stem have been made.

Classification of natural durability

The usual methods to determine the natural durability of wood species are laboratory decay tests using wood-rotting fungi and field tests in ground contact (which exposes them to termites in the tropics) or above-ground conditions (EN 350 2016; JIS Z 2101 1994; ASTM D 2017-05 2005; AWPA E7-21 2023; AWPA E9-21 2023). Furthermore, studying wood durability in relation to heartwood formation has been increasing recently (Fernández-Sólis et al. 2018; Lukmandaru et al. 2021; Martha et al. 2022).

According to the rating system by Osborne (1970), only the outer and middle heartwood were "durable" in general for both plantation and natural teak specimens. However, the inner heartwood would be "moderately durable", and the pith would be "slightly durable" (table II). It has been well recognised for numerous tree species that the outer heartwood has more decay resistance than that of the inner heartwood near the pith because of its higher contents of extractives (Rowe 1989).

Proportion of heartwood at different ages

The heartwood percentage of discs with 18, 106, 245 growth rings was 69, 87, 88%, respectively, in this study. Bhat (1998) showed the heartwood percentage at breast height of fast, medium, and slow growth rates of teak at different ages of 13, 21, 55, and 65 years in India was around 38~58, 54~63, 81~82, and 81~85%, respectively, and evidently fast-growing genetically superior trees will produce either a higher or almost the same amount of heartwood as medium and slow-growing ones. The heartwood percentage of 18 growth rings plantation disc was 69% which was slightly larger than this literature, and that of 106 or 245 rings natural discs was not much different from 65 years plantation wood. The age of the tree had a distinctive influence on heartwood proportions, as indicated by the following expression: Heartwood proportion (%) = 68.569-518.416/age, it revealed, based on the data of ages 7, 11, 16, 21, 25, 32, and 50 years, that heartwood proportion was only 3, 12 and 27% for trees aged 7, 11 and 16 years, respectively (Hamza 1997). Prediction models were developed for sapwood thickness, heartwood radius, maximum heartwood height, heartwood percentage, and heartwood volume relative to tree age in plantation teak trees ranging from 2 to 22 years. These models showed Coefficients of Determination of 70%, 90%, 95%, 73% and 31%, respectively (Fernández-Sólis et al. 2018). Further improvements in prediction accuracy are expected, especially in heartwood percentage and heartwood volume in more mature plantation wood.

Variation of decay durability across the stem related to juvenile wood

Decay durability was variable depending on the radial positions of heartwood. The inner heartwood (juvenile wood), including the pith, was less decay-resistant than the outer and middle heartwood, both in plantation wood and natural wood (table II). The radius of inner heartwood was around 6, 9, and 10 cm in plantation wood, natural (No.1) and natural (No. 2) wood, respectively. From the many reviews on teak juvenile wood (Bhat et al. 2001), such juvenile wood properties were characterised by anatomical structures such as wide rings, short fibres, small cell diameter, or wide microfibrillar angle, while juvenility in plantation-grown teak extends up to 15 or 20-25 years, depending on growth rate and individual tree and plantation site (Bhat et al. 2001). The proportion of juvenile wood in plantation-grown teak at breast height is 80-100% and 25% at ages 20 and 60 years, respectively. It is important to be fully aware of the nondurable juvenile wood located in the central part of heartwood. If nondurable teak products enter the market, it would be a disadvantage to the brand power of teak products. It is said that teak is arguably the most economically important and most famous of the tens of thousands of tropical woods (Hartshorn and Peralta 2013). The branding of natural resources was discussed, as a case study of teak wood, exploring how teak has sustained its branding through the historical and geographical entanglements of the British Empire and Burma, as a former colony, which is a prime country for teak products (Bryant 2013).

Conclusions

The inner heartwood (juvenile wood), including the pith, was obviously less decay resistant than the outer and middle heartwood, and, based on this preliminary study, there seem to be no distinctive differences in the decay resistance of heartwood, both in plantation-grown and naturally-grown teak wood. This study needs to be reinforced by additional testing, including more trees from various plantations and forest areas. In the future, while small-sized, fast-grown teak wood will constitute a significant proportion of the international teak trade, some plantations should maintain a relatively long harvesting period of more than 60 years in order to secure or develop high brand value for teak products. It is also crucial that forest management techniques, including tree breeding and wood science, be pursued to improve the properties of the immature heartwood, not only for fungi but also for termites.

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Access to data

The data used is not freely accessible.

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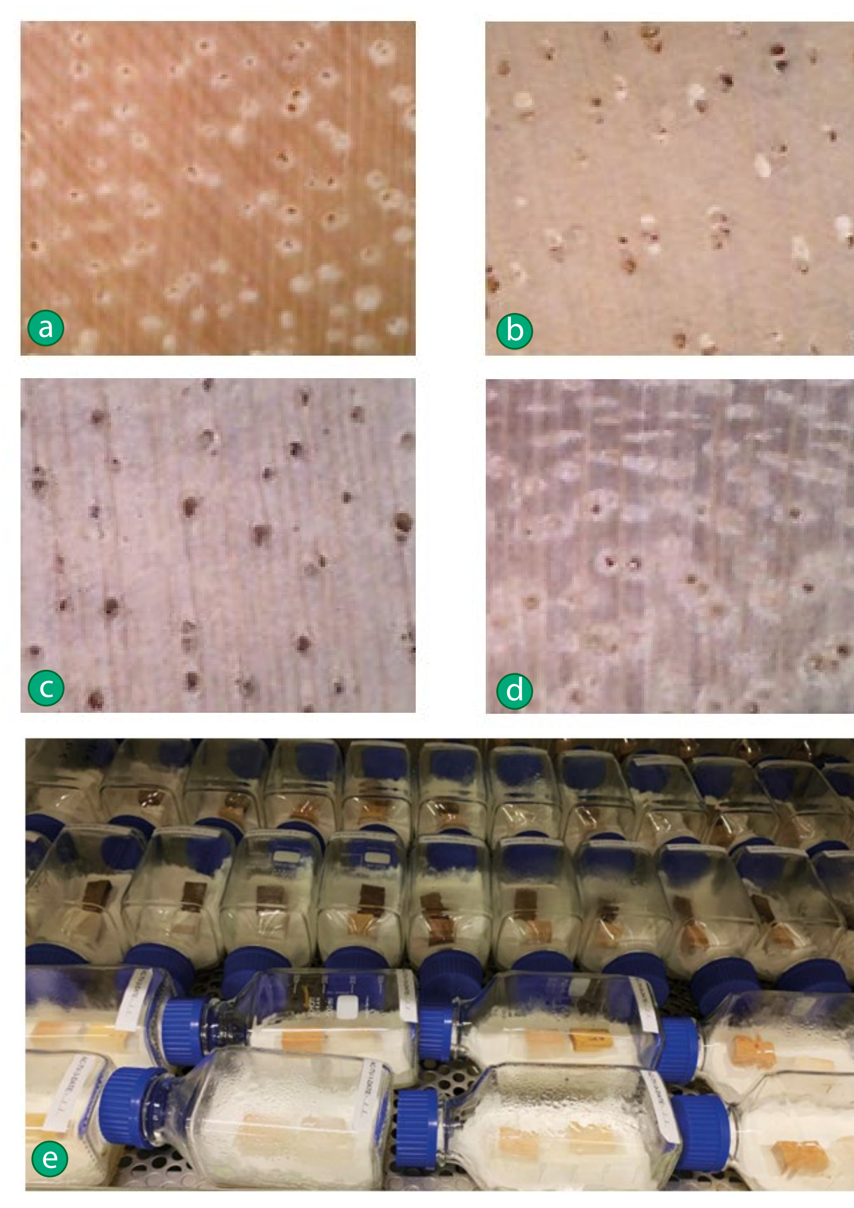
Unlocking the potential of fast-growing species from Indonesia: durability and sorption aspects



Photos 1.
Cross sections of *Acacia mangium* (a), *Anthocephalus cadamba* (b), *Paraserianthes falcataria* (c), and *Paulownia tomentosa* (d) woods.
Wood durability and resistance tests against basidiomycete fungal attack (e).
Photos S. Fauziyyah.

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RÉSUMÉ

Exploiter le potentiel des espèces à croissance rapide d'Indonésie : durabilité et sorption

La foresterie sociale ou communautaire a été promue comme une piste intégratrice pour atténuer le changement climatique, dans le cadre du programme REDD+ de la CCNUCC (Réduction des émissions dues à la déforestation et à la dégradation des forêts). Les essences à croissance rapide sont peu exploitées en foresterie communautaire en Asie du Sud-Est, alors que leur potentiel pourrait contribuer à satisfaire la demande de bois de sciage en forte croissance. En 2016, le gouvernement indonésien s'est fixé pour objectif de céder des concessions totalisant 12,7 millions d'hectares à la foresterie communautaire, objectif qui reste fortement soutenu au niveau national. Si les essences commerciales de plantation, principalement le sengon (*Paraserianthes falcataria* L. Nielsen) et le jabon (*Anthocephalus cadamba* Roxb.), sont en forte demande, le potentiel d'autres essences, telles que l'acacia (*Acacia mangium* Willd.), mérite d'être exploré. Le paulownia (*Paulownia tomentosa* (Thunb.) Steud.) a également été utilisé dans cette étude. Physiologiquement, les essences à croissance rapide diffèrent des bois durs à longue rotation par leur qualité, notamment vis-à-vis de leur résistance à la biodétérioration. Dans cette étude, la durabilité naturelle des espèces à croissance rapide susmentionnées a été étudiée en laboratoire, en utilisant des monocultures de basidiomycètes. Des échantillons de bois ont été exposés à la pourriture brune (*Coniophora puteana*) et blanche (*Trametes versicolor*) pendant 16 semaines. Des paramètres tels que la perte de masse, la dureté de la surface, les propriétés de sorption et les caractéristiques anatomiques après exposition aux champignons ont été déterminés. Les temps de mesure de la sorption à haute température étaient plus rapides et l'hystérésis plus faible. Différents niveaux d'humidité relative ont affecté les modifications de la surface totale des vaisseaux. Parmi les essences à croissance rapide, *A. cadamba, P. falcataria* et *P. tomentosa* ont été classées comme peu durables à non durables, tandis que *A. mangium* a été classé comme durable. Les données concernant les échantillons exposés à *C. puteana* se sont avérées très variables. La dureté axiale restante des échantillons de bois incubés avec *T. versicolor* était inférieure à celle de *C. Putanea*. L'observation EDX (spectroscopie de rayons X à dispersion d'énergie) a montré que K (potassium) était le cation principal dans les échantillons atteints de pourriture.

Mots-clés : basidiomycetes, durabilité inhérente, résistance à l'humidité, bois dur tropical, Asie du Sud-Est.

ABSTRACT

Unlocking the potential of fast-growing species from Indonesia: durability and sorption aspects

Social or community-managed forestry has been promoted as an inclusive way of mitigating climate change, under the UNFCCC's REDD+ programme (Reducing Emissions from Deforestation and forest Degradation). Fast-growing wood species are one of the least tapped social forestry commodities in Southeast Asia, and they have the potential to be upscaled to meet the surge in demand of sawn timber. In 2016, the Government of Indonesia aimed to hand over concession rights to 12.7 million hectares for community forestry, and support at the national level is currently strong. The highly demanded commercial species from plantations are sengon (*Paraserianthes falcatria* L. Nielsen) and jabon (*Anthocephalus cadamba* Roxb.), another interesting species to explore is acacia (*Acacia mangium* Willd.). Paulownia (*Paulownia tomentosa* (Thunb.) Steud.) was also used in this study. Physiologically, fast-growing wood species differ from long-rotation hardwoods in their quality, i.e. their resistance to biodeterioration. In this study, the natural durability of the aforementioned fast-growing species was investigated by laboratory testing, using basidiomycete monocultures. Wood specimens were incubated with brown rot (*Coniophora puteana*) and white rot (*Trametes versicolor*) fungi for 16 weeks. Parameters such as mass loss, surface hardness, sorption properties, and anatomical characteristics after exposure to the fungi were determined. Sorption measurement times at high temperature were faster with lower hysteresis. Different relative humidity levels affected the changes in the total vessel area. The fast-growing wood species *A. cadamba*, *P. falcataria*, and *P. tomentosa* were classified as slightly durable to non-durable, except for *A. mangium,* which was classified as durable due to portions of heartwood in the samples. The data for specimens exposed to *C. puteana* were found to be highly variable. The remaining axial hardness of wood specimens incubated with *T. versicolor* was lower compared to *C. Putanea*. EDX observation (energy-dispersive X-ray spectroscopy) showed K (potassium) as the major cation in decayed specimens.

Keywords: basidiomycetes, inherent durability, moisture performance, tropical hardwood, South-East Asia.

RESUMEN

Explotación del potencial de las especies de crecimiento rápido de Indonesia: aspectos de durabilidad y sorción

La silvicultura social o comunal se ha promovido como una forma inclusiva de atenuar el cambio climático, según el programa UNFCCC's REDD+ (reducción de emisiones de la deforestación y degradación forestal). Las especies madereras de crecimiento rápido se utilizan poco como recurso forestal comunitario en el sudeste asiático, a pesar de que su potencial podría ayudar a satisfacer el aumento en la demanda de madera aserrada. En 2016, el Gobierno de Indonesia se marcó como objetivo transferir los derechos de concesión de 12,7 millones de hectáreas para silvicultura comunitaria, y este objetivo a nivel nacional se mantiene en la actualidad. A pesar de la elevada demanda de especies comerciales procedentes de plantación, como el sengon (*Paraserianthes falcataria* L. Nielsen) y el jabon (*Anthocephalus cadamba* Roxb.), el potencial de otras especies, como la acacia (*Acacia mangium* Willd.), merece ser explorado. También se utilizó la paulonia (*Paulownia tomentosa* Thunb.) en este estudio. Fisiológicamente, las especies madereras de crecimiento rápido difieren de las maderas duras de rotación larga en su calidad, por ejemplo, la resistencia al biodeterioro. En este estudio, la durabilidad natural de las especies de crecimiento rápido mencionadas anteriormente se investigó mediante pruebas de laboratorio, utilizando monocultivos de basidiomicetos. Los ejemplares de madera se incubaron con hongos de pudrición parda (*Coniophora puteana*) y de pudrición blanca (*Trametes versicolor*) durante 16 semanas. Se determinaron parámetros como pérdida de masa, dureza superficial, propiedades de sorción y características anatómicas después de la exposición a los hongos. Los tiempos de medición de sorción a elevada temperatura fueron más rápidos con menor histéresis. Diferentes niveles de humedad relativa afectaron a los cambios en la superficie total de los vasos. Las especies madereras de crecimiento rápido *A. cadamba*, *P. falcataria* y *P. tomentosa* se clasificaron de no muy duraderas a no duraderas, excepto *A. mangium*, que se clasificó como duradera. Se encontró que los datos para las muestras expuestas a *C. puteana* eran altamente variables. La dureza axial remanente de las muestras incubadas con *T. versicolor* fue inferior comparada con las de *C. Putanea*. Las observaciones mediante EDX (espectrometría por dispersión de energía de rayos X) mostraron que K (potasio) era el catión principal en las muestras descompuestas.

Palabras clave: basidiomicetos, durabilidad inherente, rendimiento con humedad, madera dura tropical, Sudeste Asiático.

Introduction

Wood as a construction material offers many benefits. Despite its environmental lead as a sustainable material for construction, lignocellulosic materials such as wood are characterised by their hygroscopic and anisotropic behaviour, as well as their varying natural durability. Wood can be particularly affected by biological deterioration agents such as wood-destroying fungi, which are negatively affecting the service life of wooden components in outdoor use. In Indonesia, the core mitigation plan in the forestry sector under the Ministry of Environment and Forestry is the development of social forestry with an emission reduction target of up to 100,930 $GgCO_{2eq}$ (MoEF 2017). The implementation of the social forestry programme as a climate mitigation action plan aimed to reduce deforestation rate, forest degradation, and enhance carbon sink (REDD+) with co-benefits on poverty alleviation and improvement of governance for empowering the local economy. Per July 2022, more than 1,000 units of forest management permits through forestry partnerships have been established, which cover a total of 571,053.42 ha of forested land for more than 150 thousand households (MoEF 2022).

Agroforestry practices under the social forestry programme are often adapted by communities around forested land to maintain the soil nutrient cycle and improve the microclimate. Among different types of tree species, deciduous trees are largely planted in Indonesia. In 2001, Indonesia ranked third among all Asian countries, with a forest plantation area of 9.9 million ha. The majority of the Indonesian plantations are dedicated to rubber, teak, pines, and *Acacia mangium* (Enters and Durst 2004). The deciduous tree species planted by community farmers in one of Sumatera's regions are Sengon/Albasia. (*Paraserianthes falcataria* Nielsen), Jabon (*Anthocephalus cadamba* Roxb.), Teak (*Tectona grandis* L.), *Ficus microcarpa* and non-woody species such as *Calamus manan* and *Bambusoideae* (Pratiwi et al. 2021). These species are planted along with coffee and cocoa plants, which have been the major export commodities from various provinces in Sumatra. Soerianegara et al. (1993) reported that the mean annual increment (MAI) for the 8–12-year-old *P. falcataria* rotation is around 10–25 to 30–40 m^3/ha. Another major species is Acacia, as about 67% of the total reported area of *A. mangium* plantations in the world are located in Indonesia (Krisnawati et al. 2011). Further deciduous lightwood species utilised in community forests and their distribution are presented in table I.

Fast-growing species resourced by regional social forestry schemes are capable of taking a prominent position in the advancing climate agenda. However, such wood species often have relatively inferior material properties, including low biological durability. When six-year-old *A. cadamba* or *P. falcataria* trees are harvested, 100% of their formed wood is, of course, juvenile (Rahayu et al. 2014). However, there are notable differences in durability between juvenile and mature wood, which makes juvenile wood questionable for use as constructive timber. As far as durability is concerned, mature wood has higher concentrations of extractives compared to juvenile wood (Forest Products Laboratory 2010). Consequently, juvenile wood usually has lower natural durability compared to mature wood. Thus, the inherent resistance against biodeterioration is critical for any future use (Brischke et al. 2012). In addition, fungal degradation rates depend on wood moisture content, on the prevalent temperature, and on the inherent durability of a given wood piece (Zabel and Morrell 2012).

Table I.
Distribution of notable low-density deciduous wood species in five major islands in Indonesia adapted from Martawijaya (2004).

Wood species		Natural forest					Plantation				
	Specific gravity	Sumatra	Java	Borneo	Sulawesi	Papua	Sumatra	Java	Borneo	Sulawesi	Papua
Paraserianthes falcataria (L.) Nielsen syn. *Albizia falcataria* (L.) Fosberg and *Albizia falcata* (L) Becker	0.33 (0.24–0.49)	x	x	x	x			x		x	x
Acacia mangium Willd.	0.50 (0.46–0.52)								x		x
Anthocephalus chinensis (Lamk.) A. Rich, ex Walp. Syn. *Anthocephalus cadamba* Miq.	0.42 (0.29–0.56)	x	x	x	x	x		x	x		
Dyera costulata Hook	0.43 (0.22–0.56)	x		x							
Macaranga hypoleuca (Reichb. F.et Zoll.) M.A syn. *Nappa hypoleuca* (Reichb.F.et Zoll.)	0.34 (0.21–0.47)	x		x							
Toona sureni	0.39 (0.27–0.67)						x	x	x	x	x
Aleurites moluccana (L.) Wild	0.31 (0.23–0.44)						x	x		x	x
Gmelina arborea Roxb.	0.47 (0.46–0.63)							x			

Table II.
Wood species used in the experiment, mean wood density (standard deviation in parentheses), and origin.

No	Species	Density (g/cm^3)	Origin
1	Sengon (*Paraserianthes falcataria*)	0.29 (0.06)	Java
2	Jabon (*Anthocephalus cadamba*)	0.48 (0.04)	Java
3	Acacia (*Acacia mangium*)	0.70 (0.12)	Borneo
4	Paulownia (*Paulownia tomentosa*)	0.30 (0.01)	Austria
5	Beech (*Fagus sylvatica*)	0.68 (0.06)	Austria

For determining the expected service life of wooden components in hot-humid environments, knowledge about the inherent natural durability is required. Therefore, preventive actions such as preservation or modification measures can be applied, to assure sufficient service life. Work has been done on the durability of fast-grown wood against termite and insect attacks, but records regarding durability against decay fungi are scarcely offered (Hadi et al. 2020; Jusoh et al. 2014). Generally, cities and regencies in Java have a high to very high decay hazard index, according to Scheffer (1971), with 47% of the cities and regencies in Java having a high decay Scheffer index and 40% of the cities in the rest of Java being classified as a moderate decay hazard region (Priadi 2011). The overall purpose of this research is to assess the suitability of three fast-grown Indonesian wood species to be potentially used for engineered wood products. In particular, this paper focuses on the vapor sorption characteristics and the inherent durability of solid wood samples.

Material & Methods

Wood origin

Various wood species (1–3, table II) were attained from different plantations in Java and Borneo, Indonesia. The tree's age ranged between five and seven years. Logs were debarked and sawn into boards. For each board, defect-free samples were cut to a size of 25 × 25 × 300 (w × h × l) mm^3, and shipped to Austria in oven-dried condition. While most of the samples consisted of sapwood only, a larger proportion of heartwood was found for the *A. mangium* samples, thus some adjustments were made for decay specimens further specified in the methodology. Additional samples from Austrian-grown *Paulownia tomentosa* (Thunb.) Steud. and beech (*Fagus sylvatica* L.) were obtained from the University of Natural Resources and Life Sciences Vienna, Austria. Information about the studied wood species is displayed in table II.

Material characterization

Wood moisture dynamics

Oven-dried wood specimens with a dimension of 25 × 25 × 50 (w × h × l) mm^3 were sanded using multiple sandpaper grit starting from 120 grit to 600. Dust residues were removed using pressurised air. Thin slices of sapwood were then sawn using a circular saw (Format-4 Formatkreissäge Kappa 550) from the cross-section planes, having a size of 25 × 25 × 1 (w × h × l) mm^3. The two final specimens were then cut to size 10 × 10 × 1 (w × h × l) mm^3 using razor blades and stored inside a desiccator prior to measurement. Sorption measurements were carried out in a DVS Advantage 1 (Surface Measurement Systems). The initial dry weight was determined at 0% RH (relative humi-

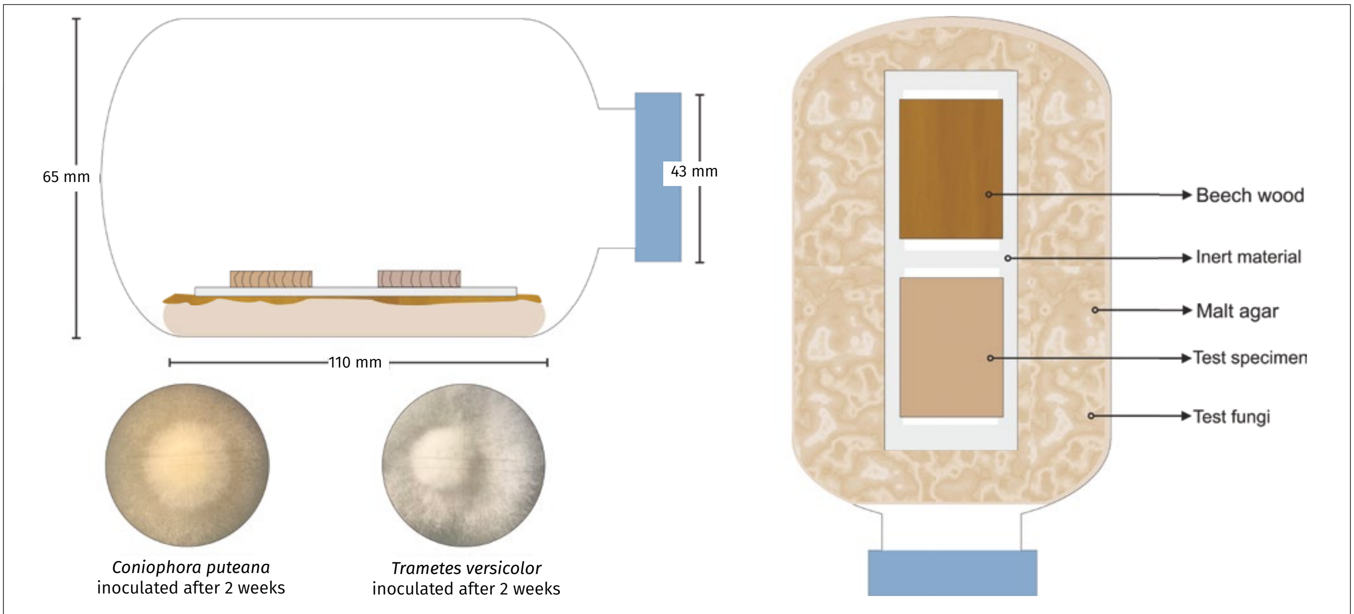

Figure 1.
Illustration of the conducted decay tests.

dity). RH levels were applied at 10% increment, from 0–90% were set, with a total of 19 RH measurement points. As soon as the dm/dt criterion of 0.002 was reached, which is the weight change over time, the next humidity level was set. Measurements were done at three different temperatures (15, 25, 35 °C) to observe potential temperature effects on the sorption properties of the materials, and the total air gas flow was set to 200 cm^3/s. Changes in vessel area were determined through image analysis, by using the public domain software ImageJ (Schneider et al. 2012).

Table III.
Durability classes (DC) of wood according to EN 350 (2016).

Durability class	Description	Median percentage mass loss (ML)
DC 1	Very durable	ML ≤ 5
DC 2	Durable	5 < ML ≤ 10
DC 3	Moderately durable	10 < ML ≤ 15
DC 4	Slightly durable	15 < ML ≤ 30
DC 5	Not durable	30 < ML

Table IV.
Testing forces for Brinell axial hardness test.

Wood species	Test fungus	Maximum load (N)
Anthocephalus cadamba	*Trametes versicolor*	400
	Coniophora puteana	30
	Control	1,000
Acacia mangium	*Trametes versicolor*	400
	Coniophora puteana	30
	Control	1,000
Paraserianthes falcataria	*Trametes versicolor*	30
	Coniophora puteana	30
	Control	1,000
Paulownia tomentosa	*Trametes versicolor*	400
	Coniophora puteana	30
	Control	1,000
Fagus sylvatica	*Trametes versicolor*	400
	Coniophora puteana	30
	Control	1,000

Decay resistance against basidiomycetes

The assessment of the biological durability of wood specimens of the selected fast-growing species was performed according to EN 113-2 (2016), using the white rot fungus *Trametes versicolor* (CTB 836 A) and the brown rot fungus *Coniophora puteana* (CBS 230.87), respectively. Both fungal strains were obtained from the culture collection of the Institute of Forest Entomology, Forest Pathology, and Forest Protection at the University of Natural Resources and Life Sciences Vienna. Before incubation, the wood specimens were sterilised using a Cobalt 60 Gammatron 1500 following EN ISO 1348 (2016) and ISO 11137 (2018). Wood test specimens (n = 13) and moisture content test specimens (n = 5) were incubated in an alternative type 1 test vessel, as shown in figure 1, for 16 weeks at 22 ± 2 °C and 70 ± 5% RH, all stored inside a Phytotron (Heraeus-Vötsch, type VB 0714). Fluctuations in temperature and RH were monitored in real-time using the Simpati® software.

Beech (*F. sylvatica* L.) wood was used for virulence control of the two test fungi, which have to lead to a minimum mass loss of 20% after 16 weeks of incubation. All test specimens were produced from sapwood, except for *A. mangium,* which also contained larger portions of heartwood. To comply with the standard dimension, specimens were made with as little heartwood as possible. After incubation, the specimens were cleaned from adhering mycelium, oven-dried at 103 ± 2 °C, until a constant weight was reached. Mass loss was determined by weighing the oven-dry specimens before and after incubation. The inherent durability was classified according to EN 350 (2016) (table III).

Brinell hardness test

Brinell hardness tests were performed according to EN 1534 (2020). After mass loss evaluation, the specimens were stored at 20 °C and 65% RH for approximately one month, until weight constancy was reached. The test was performed with a universal testing machine Zwick Roell Z020. With an element length of less than 200 mm based on the testing norm, one testing point on the axial plane or face element was performed on each of the exposed as well as the control specimens. The hold and release of the hardness indenter were set to 30 seconds. The Brinell hardness (HB) was calculated using Equation 1:

$$HB=\frac{2F}{\pi D\left(D-\sqrt{D^2-d^2}\right)} \qquad \text{(Equation 1)}$$

where F is the maximum load (N), D is the diameter of the indentation ball (mm), and d the diameter of residual indentation (mm). A list of predetermined forces used for the measurements is shown in table IV.

Characterization of fungal decay

The level of fungal degradation after incubation on decayed specimens was observed using the digital microscope Olympus DSX 1000 and a scanning electron microscope (SEM Hitachi HT3030). Samples were prepared using a sliding microtome, by cutting tangential and longitudinal sections. Traces of fungal decay were preliminarily

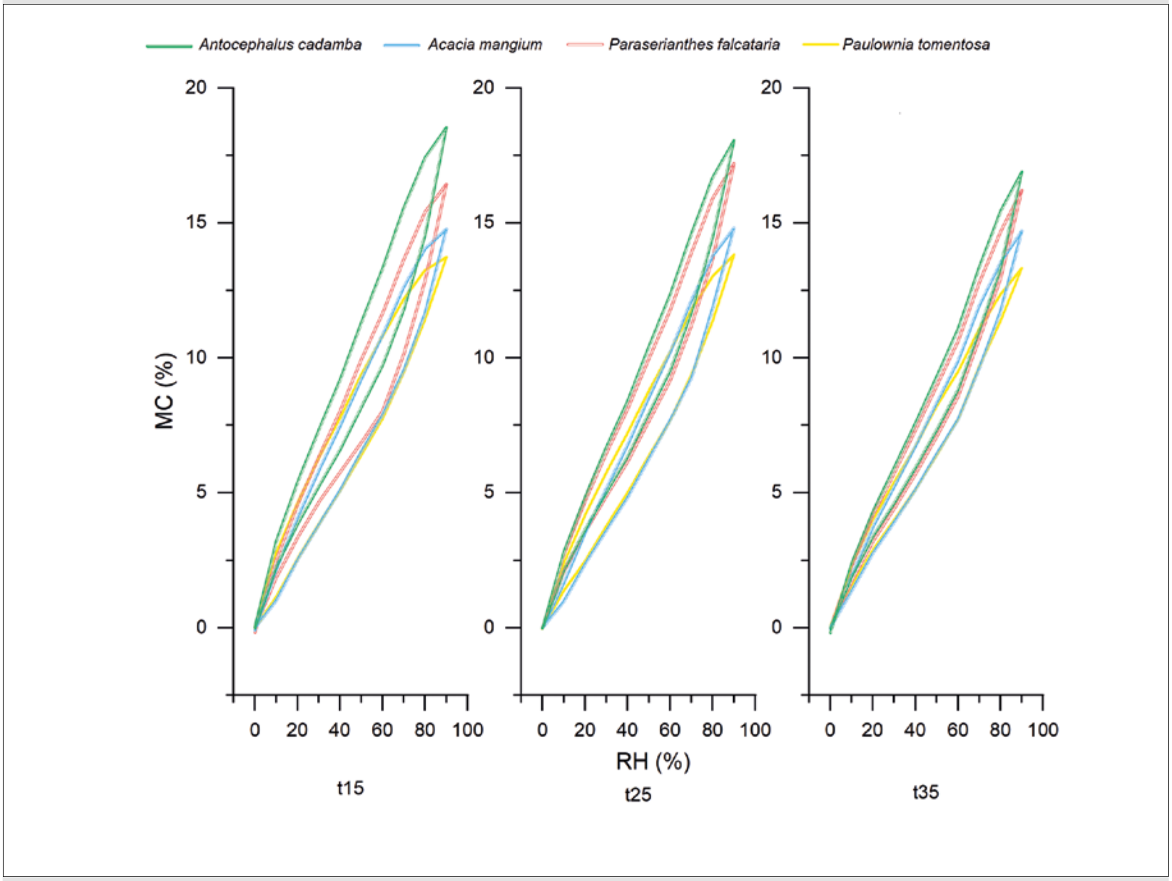

Figure 2.
Sorption isotherms of wood species at different temperatures of 15, 25, and 35 °C.

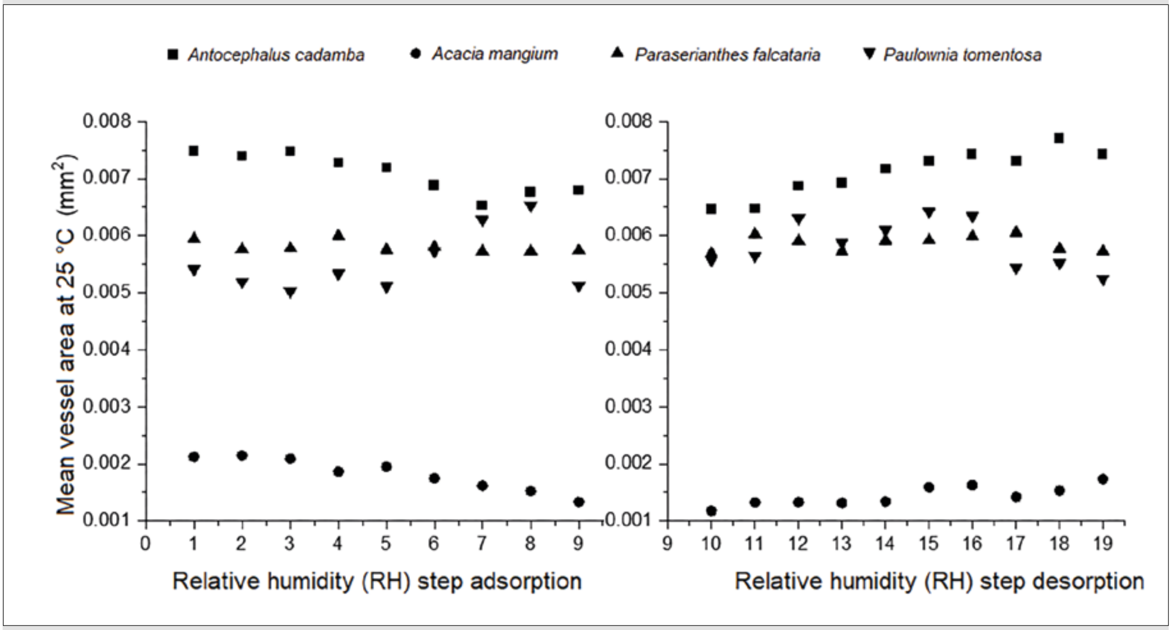

Figure 3.
Mean vessel area of wood specimens at different relative humidity (RH) steps.

observed using an energy-dispersive X-ray spectrophotometer (EDX), which was implemented in the SEM. The EDX was used to perform elemental analysis on the specimens.

Results and Discussion

The exploration of unutilized fast-growing wood species from secondary forests in Kalimantan has been studied to understand their fibre characteristics and potential utilisation in various wood products, including construction materials (Adi et al. 2014). Fast-growing wood species generally have lower density and shorter fibre length compared to slow-growing wood species (Kojima et al. 2009). They have a higher proportion of early wood, which is more susceptible to moisture movement, leading to splitting and cracking (Gril et al. 2017). Nevertheless, as an oriented strand board, they meet minimum requirement for OSB/2 properties (Dumitrascu et al. 2020). Before utilising wood species as local building materials, information regarding their properties such as strength, dimensional stability, and inherent durability in relation to sorption isotherms is vital for efficient practical use (Wegner et al. 2010). The variability of the sorption isotherm, which helps us understand how wood will absorb and release moisture, can have an impact on the durability of fast-growing wood species (Lee et al. 2021; Zhang and Richman 2021).

In this study, sorption isotherms show total vapour adsorbed by the samples as a function of relative vapour pressure (Nopens et al. 2019). All four examined fast-growing wood species showed similar characteristics, by following the IUPAC classification type II isotherm. In figure 2, smaller hysteresis were noted at the higher temperature levels. Thus, results indicated that temperature and wood species had a significant influence on wood hysteresis and sorption isotherm. This is in accordance with Krupińska et al. (2007), who also found that wood became less hygroscopic when measurement temperature increased, as indicated by decreased moisture content. This phenomenon resulted from enhanced reaction rates due to higher water activity (Panchariya et al. 2001). Moreover, the width of the hysteresis loop depends on internal bonding between and among the cell wall polymers (Irbe et al. 2006). Higher measurement temperatures also reduced the sorption hysteresis of all wood samples, especially in the high humidity range, with a maximum hysteresis seen at 60–70% RH. The highest to lowest moisture contents at 90% RH were found in the following order: *A. cadamba* (highest), *P. falcataria*, *A. mangium*, and *P. tomentosa* (lowest). Total time to achieve equilibrium required the longest period at the RH 90%, for all measured temperatures and across all wood species. The total running times of the four-wood species were different at each set temperature, with the longest sorption period found for *A. mangium*, followed by *A. cadamba*, *P. falcataria*, and by *P. tomentosa*.

In this study, vessel area changes have been observed during swelling and shrinking at the different RH levels (figure 3). The changes in vessel area were following wood activity, depending on the adsorption and desorption stages. The graph shows that the mean vessel area was decreasing during the adsorption cycle, while on the desorption cycle, it tended to increase. Different moisture contents were recorded, and a relationship between initial mass and moisture contents was made at the end of each RH step. A previous study on cell wall structure and sorption properties using different drying methods, i.e. air drying and oven drying, showed that the higher shrinkage corresponded to a smaller surface area. In this study, the surface area of the cell wall was correlated to the total pore volumes (Broda et al. 2021).

With respect to the species resistance against decay, the specimens were classified as slightly durable to not durable (DC 4–5). The average mass losses of wood specimens exposed, from highest to lowest, irrespective of fungal species, were as follows: *A. cadamba*, *P. falcataria*, *P. tomentosa*, and *A. mangium* (table V). This is expected for fast-growing wood species, which have a high proportion of juvenile wood within the sapwood (Darmawan et al., 2013). Fast-growing wood species with short rotation periods contain high portions of juvenile wood, which means lower resistance against decay, due to fewer extractives and lower technological properties. The high proportion of juvenile wood negatively impacts wood quality and durability against biodeterioration agents (Hadi et al. 2015; Lasserre et al. 2009).

Acacia mangium behaved differently since the samples also included smaller portions of heartwood. Heartwood-free samples were not available when the specimens were procured with small-diameter acacia. To comply with the requirement of a minimum sample dimension based on EN 113-2 (2021), specimens had to be made with sapwood close to heartwood. In the literature, mass losses of *Acacia* hybrid, *A. mangium*, and *A. auriculiformis* due to decay by *T. versicolor* were 10.2%, 11.2%, and 7.3%, respectively (Jusoh et al. 2014). Those results were higher compared to the data found in this study, which had a mass loss of only 2.7% after exposure to the same white rot species. An even greater mass loss value of 14.3% was presented by another study on *A. mangium*, as exposed to *T. versicolor* (Wahab et al. 2017). *Acacia mangium* used in this study had a slightly higher wood density (0.70 g/cm^3), compared to *A. mangium* from Malaysia forest plantations (0.29–0.58 g/cm^3). Similar results as in the present study were found by Krisnawati et al. (2011), who found that *A. mangium* from natural forest in Indonesia had a density ranging between 0.45–0.69 g/cm^3, at 15% moisture content.

Figure 4 shows mass losses of the wood specimens due to decay caused by the white rot fungus *T. versicolor* and the brown rot fungus *C. puteana* after 16 weeks of exposure, including the mass losses of wood specimens of *F. sylvatica*, which were included in order to prove the virulence of the used test fungi. There was no notable difference in durability classes between brown-rot and white-rot decay; however, brown-rot exposure resulted in

Table V.
Mean density (ρ), mean moisture content before (μMC_{be}) and after incubation (μMC_{ae}), mean mass loss (µML) and durability classes (DC) based on median ML of wood specimens (standard deviation in brackets).

Wood species	Fungal species	Measured parameters				
		ρ (g/cm3)	µMCbe (%)	µMCae (%)	µML (%)	DC
Anthocephalus cadamba	*Trametes versicolor*	0.50 (0.04)	6.56 (0.79)	78.10	34.4 (7.7)	5
	Coniophora puteana	0.48 (0.06)	6.63 (0.61)	70.00*	27.6 (4.3)	4
Acacia mangium	*Trametes versicolor*	0.78 (0.05)	7.81 (0.9)	51.81	2.7 (2.5)	1
	Coniophora puteana	0.76 (0.08)	8.4 (0.88)	68.53	2.1 (0.1)	1
Paraserianthes falcataria	*Trametes versicolor*	0.29 (0.06)	5.29 (0.72)	71.67	29.2 (7.4)	4
	Coniophora puteana	0.31 (0.06)	2.7 (9.91)	70.00*	15.1 (12.3)	4
Paulownia tomentosa	*Trametes versicolor*	0.30 (0.01)	6.26 (0.68)	76.60	23.6 (8.9)	4
	Coniophora puteana	0.29 (0.02)	6.2 (0.02)	70.00*	10.6 (18.8)	3v
Fagus sylvatica	*Trametes versicolor*	0.71 (0.04)	4.11 (0.46)	54.62	35.9 (9.5)	Virulence
	Coniophora puteana	0.70 (0.02)	3.9 (0.29)	71.72	53.3 (3.5)	Virulence

* waterlogged test specimens; "v" indicates the species exhibits high level of variability.

higher mass loss variation within the species. High data variability was recorded on *P. falcataria* and *P. tomentosa* exposed to *C. puteana*, with standard deviations between 12.3% and 18.8%. A former study indicated that the variation in mass loss data could be due to internal factors such as natural resistance across the wood specimens and the selectivity of the decaying fungi (Sharapov et al. 2018).

The results of the Brinell hardness tests on the wood samples are presented in figure 5. Axial hardness values before and after exposure were significantly different ($p < 0.05$). Species exposed to *T. versicolor* had considerably lower axial hardness compared to *C. puteana*. Species with the highest axial hardness values after incubation with basidiomycetes were from high to low: *A. mangium, A. cadamba, P. falcataria,* and *P. tomentosa,* regardless of decay type. When compared to control specimens, the axial hardness of specimens decayed by *T. versicolor* was reduced by 0.07%, 69.04%, 45.61%, and 55.34% for *A. mangium, A. cadamba, P. falcataria,* and *P. tomentosa,* respectively. Specimens exposed to *C. puteana* had slightly lower percentages of axial hardness reduction of 0.04%, 57.74%, 17.30%, and 22.24%. Brinell axial hardness is strongly influenced by the density of the surface layer, while variation in density within the sample did not influence these properties (Rautkari et al. 2013).

Test specimens exposed to brown rot revealed noticeable degradation compared to white rot in the wood substrate. Even though brown rot is causing more visible damage, the average mass loss of specimens decayed by *T. versicolor* was higher compared to *C. puteana*. Lignin plays a major role in wood degradation caused by fungi. It provides biological protection by generating enzymes to avoid fungal penetration (Arantes et al., 2011). Lignin in gymnosperms consists mostly of guaiacyl units, while angiosperms are composed of syringyl and guaiacyl units in varying ratios (Whetten and Sederoff 1995; Wool 2005). Thus, hardwood possesses lower resistance to white rot decay, which mainly attacks lignin. Additionally, fungal selectivity in degrading wood substrates is different depending on species. *T. versicolor* initially attacks hemicellulose and lignin, which causes strength reduction, whereas brown rot fungi only decompose hemicellulose or cellulose selectively (Qi et al. 2022).

Decay and active hyphae from fresh incubated specimens are shown in figure 6. White-rot decay activity has produced more porous zones in wood tissue, which led to the disintegration of wood samples (figure 6a). Fungal access to adjacent cells most likely took place via pit apertures or through direct penetration via cell walls (Schwarze 2007). In this study, hyphae spread through adjacent vessels (figure 6b), with the vessels filled with fungal mycelia. Cracks often occur between the radial cell walls close to the vessels. In figure 6b it is seen that hyphae grew inside the cell lumina with close contact to the cell walls. Here, active hyphae excrete degrading enzymes, causing a reduction in wall thickness over time (Schmidt 2006).

In figures 6d-f, characteristics of wood decay by *C. puteana* are displayed. The interface of *C. puteana* in *P. falcataria*'s lumen can be seen in figure 6d. Changes in

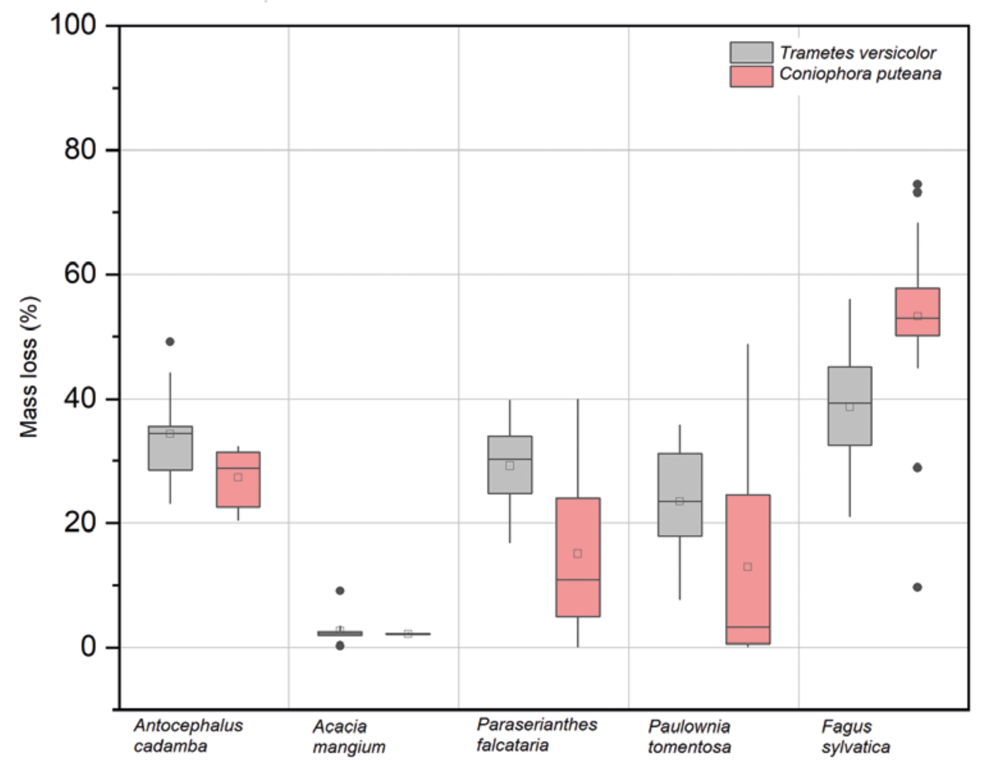

Figure 4.
Mass loss results of white rot and brown rot decay after 16 weeks exposure.

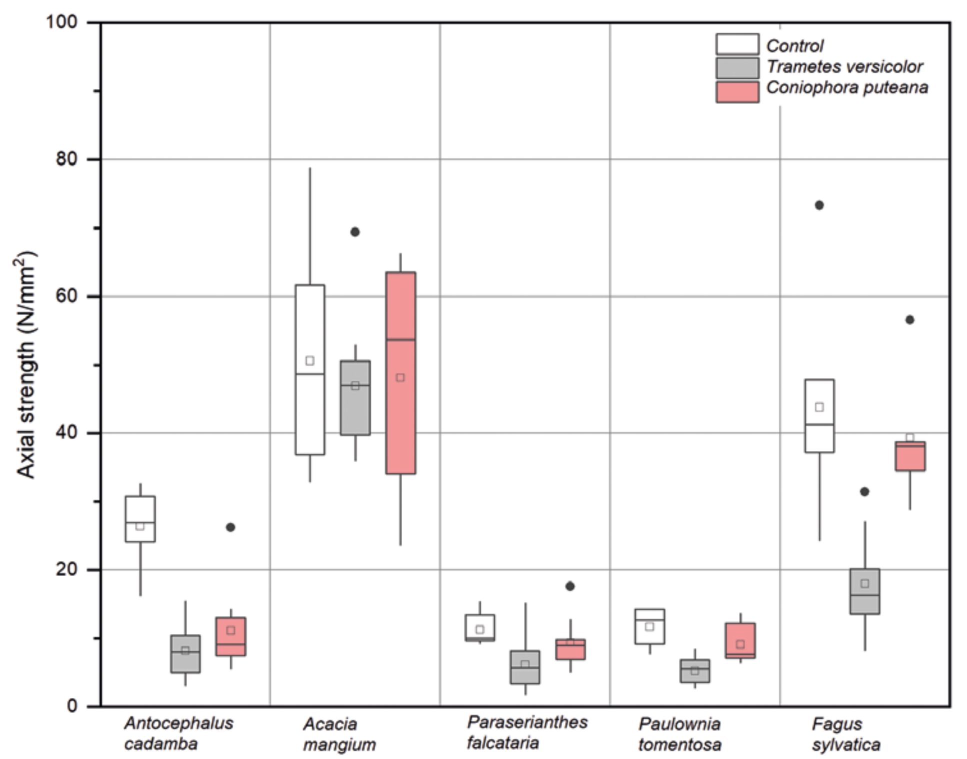

Figure 5.
Changes in axial hardness of decayed test specimens after 16 weeks exposure.

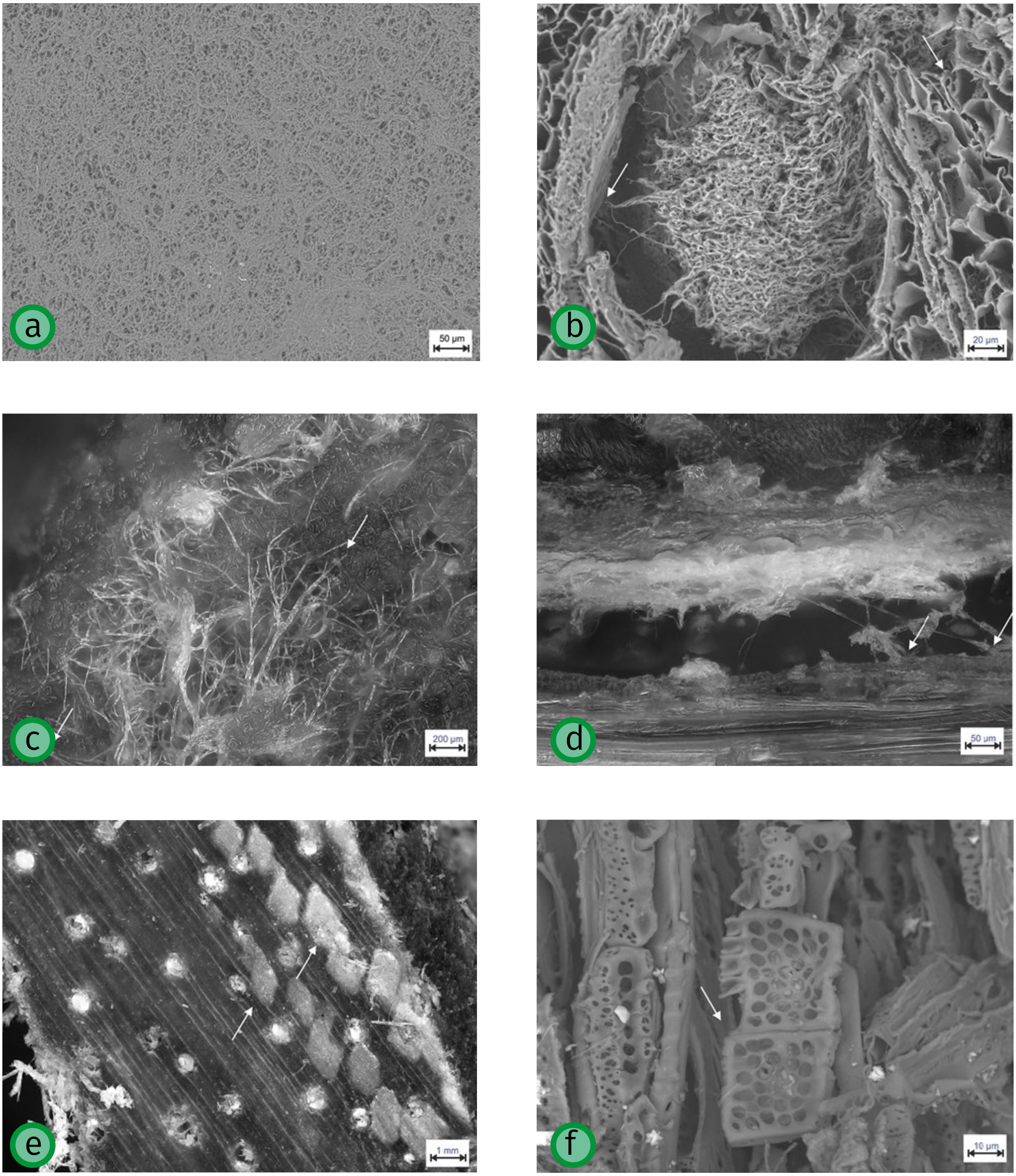

Figure 6.
Mycelium mats of *Trametes versicolor* on *Paraserianthes falcataria* 200x magnification (a), bundles of *T. versicolor* on *P. falcataria* 100x magnification (b), hyphae of *T. versicolor* on *P. falcataria* 40x magnification (c), *Coniophora puteana* mycelium adherence interface on *P. falcataria* (d), structural changes on *P. falcataria* decayed by *C. puteana* 40x magnification (e) and cuboid cells on *Anthocephalus cadamba* decayed by *C. puteana* 600x magnification (f).

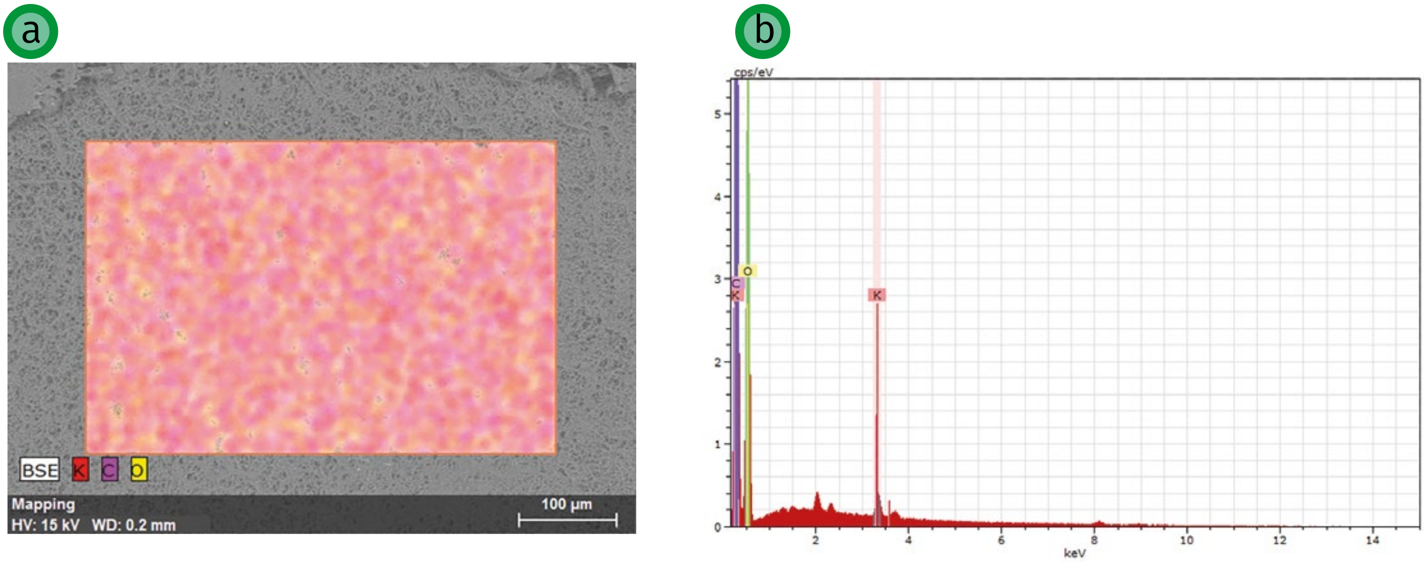

Figure 7.
EDX analysis on a sample degraded by *Trametes versicolor*.

wood occurred due to the degradation of wood components by degrading enzymes of brown rot (figures 6e-f). Disintegration of cell walls is a result of extensive degradation of cellulose and hemicelluloses, subsequently causing the formation of holes and cracks (Moskal-del Hoyo et al. 2010). Changes in components degraded by white-rot decay caused severe changes in impact bending due to significant carbohydrate losses (Bari et al. 2015). Brown-rot decay is causing a significant decrease in the weight and mechanical properties of a given wood piece (Bouslimi et al. 2014). According to Pandey and Pitman (2004), decay by *C. puteana* causes the lignin content to increase with exposure time, in parallel with a mass loss as the carbohydrates are selectively removed.

Using the EDX method, major portions of K (potassium) cations were found on decayed wood specimens degraded by *C. puteana* or *T. versicolor* (figure 7). Higher concentrations of Ca (calcium), Mn (manganese), and Fe (iron) in decayed wood were also found in the study of Jellison et al. (1992). Ostrofsky et al. (1997) reported that Ca and K tend to increase with fungal exposure, as seen in red spruce. A higher K cation concentration is also associated with a decrease in the electrical resistance of decaying wood (Gao et al. 2019). Increased cation concentrations are correlated with mass loss and the progression of wood decay (Soge et al. 2021). Fungal activity on wood includes the transport of ions towards the infected regions. Recent findings suggested an increase in Fe concentration in brown rot decayed specimens, with significant movement of Ca from sound wood cell walls into the area colonised by fungal mycelium (Kirker et al. 2017).

Engineered wood products, such as glued laminated timber (glulam) or oriented strand boards (OSB), can be derived from tropical fast-growing wood species. For example, Hadi et al. (2021) studied polystyrene-impregnated glulam made from tropical wood species and found mechanical properties such as MOE and MOR to be inferior, which means they did not meet the required standards. Baskara et al. (2022) tested OSB made from the tropical fast species *Paraserianthes falcataria*, *Maesopsis eminii*, and *A. mangium*. It was found that with sufficient isocyanate resin as the binder for OSB, most of the physical and mechanical properties did meet the standard.

The use of tropical fast-growing wood species in engineered wood products is an important area of research, given the potential for these species to serve as a valuable resource. In their solid form, wood durability, axial hardness, and sorption properties are important factors to consider when selecting fast-growing wood species for practical applications commensurate to its service life (Barbu et al. 2022; Missio et al. 2016). Wood durability is affected by its natural resistance to decay, which varies among species. Meanwhile, sorption properties are an important analytical tool for the characterization of wood or any construction materials where the impact of humidity is important to material performance. The moisture content of wood is an important parameter influencing almost all mechanical properties of wood, and strength properties of wood increase as its moisture content decreases (Cao et al., 2021). The information regarding inherent durability and sorption properties leads to a better understanding of the provision of engineered wood products made from fast-growing species, which will be the avenue for the next research activities.

Conclusions

In this study, fast-growing wood species showed low resistance to decay by basidiomycetes. Tested low-density wood had a high affinity for water. Moreover, higher temperatures during vapour sorption have led to faster running times and less expressed sorption hysteresis. The longest time period to reach moisture equilibrium was found at a relative humidity of 90%. Among the observed wood species, *Anthocephalus cadamba* had the highest moisture content. Changes in vessel area at different relative humidity (RH) levels were in accordance with the adsorption and desorption stages. Concerning decay resistance, specimens exposed to brown rot (*Coniophora puteana*) showed a higher mass loss variation within the tested species, compared to white rot (*Trametes versicolor*). Based on the obtained results, durability classes of wood were classified into durability classes 4–5 (slightly durable–nondurable), with the exception of *Acacia mangium*, which was rated as very durable (class 1). The unexpected result for *A. mangium* was due to the small proportions of heartwood present in the specimens. Specimens exposed to *T. versicolor* exhibited significantly lower axial hardness, whereas those exposed to *C. puteana* showed visibly extensive degradation compared to *T. versicolor*. High K ion concentrations were detected in decayed regions of the wood specimens. These results are crucial in determining further steps employing strategies to improve observed wood species properties for structural components in various conditions.

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Data access
Following the FAIR (Findable, Accessible, Interoperable, and Reusable) principle, the data used in this article is available based on request and downloadable on doi: https://doi.org/10.5281/zenodo.8430111

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Writing – Original Draft Preparation	S. Fauziyyah
Writing – Review & Editing	S. Fauziyyah, C. Brischke, R. Wimmer, E. Halmschlager

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Survey on the natural resistance to decay of five hundred tropical wood species

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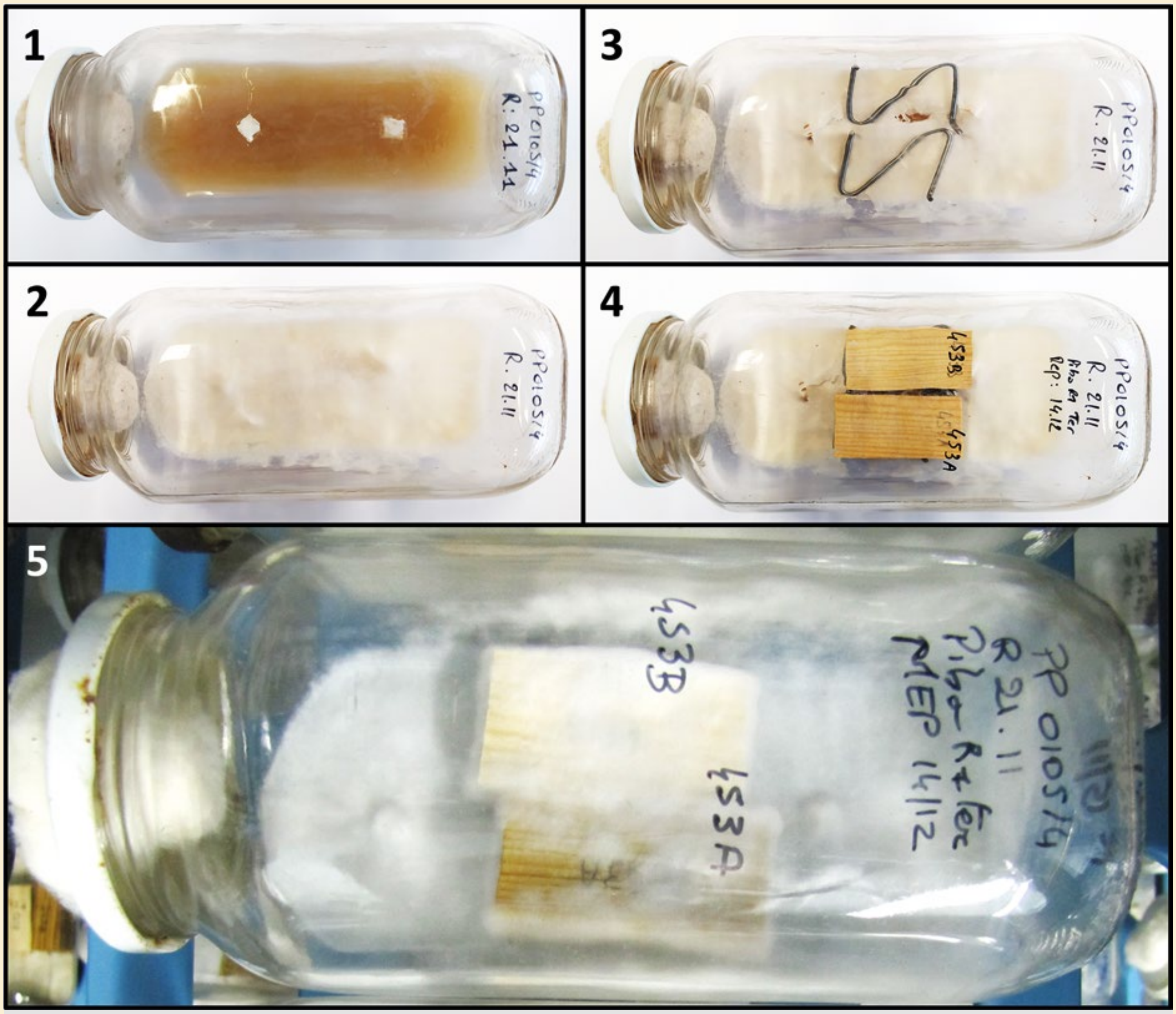

Photos 1.
Agar test in French squared glass bottles. (1) Yellow agar bed is inoculated with two white pieces of desired fungi from stock culture. (2) Mycelium has covered the whole agar bed. (3) Two Z-shaped sterilized metal supports are placed upon the mycelium bed. (4) Two wood blocks are placed upon the metal supports. (5) French squared glass bottle with perforated metal cap closed by a wad of cotton wool. Mycelium covers the two wood blocks.
Photos K. Candelier.

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RÉSUMÉ

Enquête sur la résistance naturelle aux champignons lignivores de cinq cents essences de bois tropicaux

La durabilité naturelle des essences de bois contre la pourriture redevient un sujet d'actualité avec d'une part l'essor des utilisations du bois en tant que matériau naturel, et d'autre part le débat sur l'utilisation de fongicides synthétiques. Au milieu du 20e siècle, de nombreuses études expérimentales ont été réalisées en Europe et en Amérique du Nord, en utilisant différents protocoles standardisés. Plus de cinq cents essences de bois tropicaux - 9842 échantillons au total - ont été testées en France entre 1955 et 1990. Il semble utile de permettre un accès libre à l'ensemble des données issues de ces tests afin d'approfondir les connaissances sur la durabilité naturelle d'un large éventail d'essences de bois. La majorité (68 %) des tests a utilisé deux protocoles légèrement différents, où seules les dimensions des échantillons de bois testés ont changé. Environ la moitié des essences ont été testées dans le cadre de l'un des deux protocoles, et l'autre moitié par le second. Par ailleurs, certaines essences ont été testées avec les deux protocoles. Les dimensions des blocs, la souche fongique utilisée et le type de bois (aubier ou duramen) donnent tous des résultats significativement différents, mais la perte de masse moyenne due aux 4 principales souches fongiques est un bon indicateur de la résistance du bois à la pourriture. Globalement, la perte de masse de l'aubier selon chacun des protocoles est plus élevée de 45 % que celle du duramen de la même essence. Il existe une corrélation positive significative entre la résistance à la pourriture de l'aubier et la résistance du duramen, mais la diminution du duramen vers l'aubier est plus importante pour les essences de bois durables que pour les non durables. La résistance à la pourriture du duramen varie fortement entre les arbres d'une même essence, à l'exception de celles classées « très durables » et « non durables ». Cela ouvre la perspective d'une classification de la résistance naturelle à la pourriture pour de nombreux types de bois utiles, mais souvent considérés comme « modérément » résistants parce qu'ils comprennent une petite proportion d'essences peu résistantes. Chacun des deux protocoles d'essais comprenaient plus d'une centaine d'essences pour lesquelles la densité et la composition chimique étaient disponibles. La densité, la teneur en lignine et la teneur en matières extractibles ont une influence similaire et très significative sur la résistance du bois à la pourriture (R^2 d'environ 0,25).

Mots-clés : composition chimique, densité, champignons, durabilité naturelle, collection de bois, essences tropicales.

ABSTRACT

Survey on the natural resistance to decay of five hundred tropical wood species

The natural durability of wood species against rot has again become a matter of interest for the uses of wood as a natural material, while the use of synthetic fungicides is being debated. In the mid-20th century, many experimental studies were performed in Europe and North America, using different standardised protocols. More than five hundred tropical wood species were tested in France between 1955 and 1990, with a total of 9,842 wood samples tested. It would seem useful to allow free access to all the data from these tests in the interests of a more comprehensive study of the natural durability of a wide range of wood species. The great majority (68%) of all these tests used two slightly different protocols with only a change in woodblock test dimensions. Roughly half of the species were tested under one of the two protocols, and the other half under the second. In addition, certain species were tested with both protocols. The dimensions of the test blocks, the fungal strain used, and the wood type (sapwood or heartwood) all give significantly different results, but the mean mass loss due to the 4 main fungal strains is a good predictor of the wood resistance to rot. Overall, mass loss for sapwood with each protocol is 45% higher than for heartwood of the same species. There is a significant positive correlation between the rot resistance of the sapwood and the heartwood, but the decrease from heartwood to sapwood is greater in durable wood species than in non-durable ones. Heartwood rot resistance was observed to be highly variable between trees of the same species, except in those classified as "very durable" and "non-durable". This opens up possibilities for a classification of natural rot resistance for numerous useful types of timber that are often regarded as only moderately resistant because they include a small proportion of species with poor resistance. Each protocol group included over one hundred species for which density and chemical composition data were available. Density, lignin content, and extractive content have a similar and very significant influence on the rot resistance of the wood (R^2 around 0.25).

Keywords: chemical composition, density, fungi, natural durability, wood collection, tropical wood species.

RESUMEN

Revisión de la resistencia natural a la descomposición fúngica de quinientas especies madereras tropicales

La durabilidad natural de las especies madereras ante la pudrición se ha convertido de nuevo en un tema de interés para la utilización de la madera como material natural, mientras se está debatiendo el uso de fungicidas sintéticos. A mediados del siglo XX se realizaron muchos estudios experimentales en Europa y América del Norte, mediante diferentes protocolos estandarizados. Se hicieron ensayos en Francia con más de quinientas especies madereras tropicales entre 1955 y 1990, en un total de 9842 muestras de madera. Parece útil permitir un acceso libre a todos los datos de estas pruebas para un estudio más completo de la durabilidad natural de una amplia gama de especies de madera. La gran mayoría (68 %) de estas pruebas utilizaban dos protocolos ligeramente distintos, con una diferencia únicamente en las dimensiones de los bloques utilizados para los ensayos. Aproximadamente la mitad de las especies se ensayaron bajo por uno de los dos protocolos, y la otra mitad por el segundo. Además, algunas especies se analizaron con ambos protocolos. Las dimensiones de los bloques de ensayo, la cadena fúngica utilizada y el tipo de madera (albura o duramen) proporcionan resultados significativamente diferentes, pero la pérdida de masa media debida a las cuatro cadenas fúngicas principales es una buena predicción para la resistencia de la madera a la pudrición. En general, la pérdida de masa en la albura con cada protocolo es el 45 % más elevada que para el duramen de la misma especie. Hay una correlación positiva significativa entre la resistencia a la pudrición de la albura y del duramen, pero el decrecimiento del duramen a la albura es mayor en las especies madereras duraderas que en las no duraderas. Se observó que la resistencia del duramen a la pudrición era altamente variable entre árboles de la misma especie, excepto en los que se califican como «muy duraderos» y «no duraderos». Esto abre posibilidades de una clasificación de la resistencia natural a la pudrición para numerosos tipos de madera útiles que se consideran a menudo solo como moderadamente resistentes porque incluyen una pequeña proporción de especies con baja resistencia. Cada protocolo se aplicó a un centenar de especies para las cuales estaban disponibles los datos de densidad y composición química. Densidad, contenido en lignina y contenido en materias extractibles tienen una influencia similar y muy significativa en la resistencia a la pudrición de la madera (R^2 aproximadamente del 0,25).

Palabras clave: composición química, densidad, hongos, durabilidad natural, colección de madera, especies de madera tropical.

Introduction

Wood represents a source of nutriments for microorganisms like fungi, and decay is a common natural way of wood degradation in forest conditions or whenever moisture content keeps high in a piece of timber (Fougerousse 1960). This is also true inside tree living parts such as the trunk or branches (Taylor et al. 2002) and each species has developed ways to limit fungal attacks so that decay of dead wood in a forest can take from a few months to many years depending on the species, tree or part of the tree (Déon et al. 1980), and climatic conditions, of course.

This natural resistance to decay (NRD) is different from conferred resistance using chemical treatments by fungicides (Fougerousse 1966) or any other wood modification processes (Gérardin 2016), but the way to test it is just the same, and standard tests for treated woods are used to quantify NRD.

The knowledge of NRD, as well as natural resistance to insects or marine borers, is key for structural design as well as mechanical resistance to external stresses (Sundararaj et al. 2015). There is much evidence of species' choices based on their NRD for long-lasting buildings in all civilizations (Scheffer and Morrell 1998).

The fast advances in chemistry during the last century provided a wide range of biocides, including efficient fungicides to protect wood pieces against decay (Fougerousse 1961). For some time, NRDs seemed less important than treatability in rich, industrialised countries. But today, pesticides are less and less accepted, and treating timbers massively takes away the advantage of environmentally friendly wood (Infodal 2013). Therefore, there is a renewed interest in the natural durability of tree species (Willeitner and Peek 1997), both in the developed northern countries and in the southern ones, where many tropical species present a good resistance against biodegradation.

Besides, as NRD is considered to be strongly influenced by the different fractions of the secondary metabolites (also called extractives) (Déon et al. 1980), durable wood species can also be a valuable source of active chemical compounds for treating fungal disease, both for plants and humans (Royer et al. 2012).

Ultimately, there is a large amount of literature about NRD, including some reviews with lists of species (Bavendamm 1960, Scheffer and Morrell 1998, Akhter et al. 2003, Sundararaj et al. 2015). But, as described by Willeitner and Peek (1997), there are many discrepancies between sources, and they even consider that "this data is of only limited value, because often no details are given on the test protocol and parameters, and no general classification system has been used to achieve comparable statements".

One of the major problems comes from the choice to publish NRD classification results instead of experimental data on well-defined laboratory or field tests. Wood durability classification depends on the author, timber use, as well as on the tree, or the position in the tree. In addition, the variation in NRD also depends on the fungus (age or health and virulence of strains for laboratory tests) or the presence and competition between fungi in the field. Thus, there can be large variability for the same species, and there is no way to understand the reasons for such divergences.

During 35 years (1953 to 1989), CIRAD [previously *Centre Technique Forestier Tropical* (CTFT, in French) until 1985] wood preservation laboratory achieved 10,400 natural decay tests, measuring mass loss for standard wood specimens against standard fungal strains, in standard laboratory conditions. All the basic information about these tests, which included maximum, minimum, and mean mass loss values for 10 specimens of the same provenance, was put in digital form in a data file. In total, 580 species were tested under different conditions: specimen dimensions, fungal exposure durations, type of wood (sapwood or heartwood), and fungal strains (6 different strains accounting for 90% of the tests, 4 various strains accounting for 75% of the tests).

There were two main test periods: before 1965 and after 1975, the main difference being the specimen dimension (figure 1 and figure 2). Between 1965 and 1974, there was an active business about the French standard for testing wood decay concerning the efficiency of treatments on treated wood decay (Afnor 1973, Afnor 1994). Since 1974, the experimental conditions (specimen dimension, duration of fungal exposure, fungal strain) have been kept constant. Between 1953 and 1965, another standard was used with a much smaller size of wood samples, but with the same duration and mainly the same fungal strain. There are approximately the same number of species (around 250) for each of the standards.

This article aims to share all these data and discuss the relationships between fungal natural durability and the density, chemical composition, species, and portion (sapwood or heartwood) of the wood.

All test results by botanical species are available in the Excel file accessible in the dataverse referenced at the end of this article.

Materials & Methods

Agar test using the French standard for testing wood decay

Wood blocks are stored in a climate chamber (20 ± 2 °C, 65 ± 5%) to share a common equilibrium moisture content (12% as a mean). For each fungal test, there is a test block and an assumedly very similar water content control block. All wood blocks are weighed at the beginning. Test blocks are sterilised (temperature or best Gamma-ray irradiation) before the decay test.

All tests are performed as follows: malt-agar is diluted in water and used as a support and initial food for fungi growth. It is deposited in French squared glass bottles

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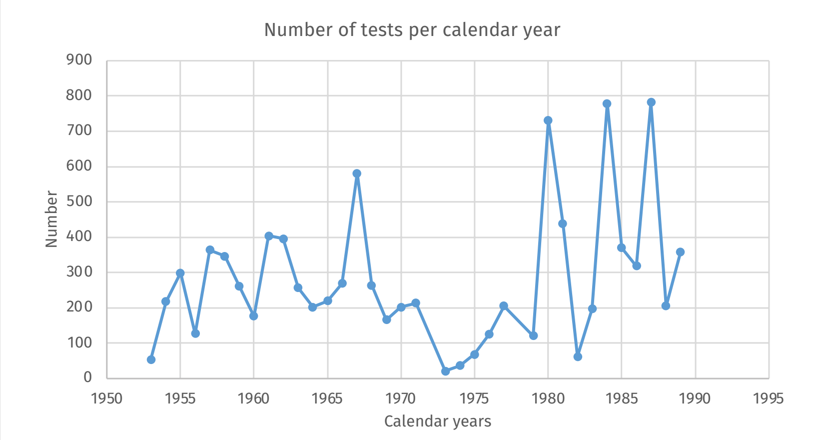

Figure 1.
History of the decay resistance tests carried out between 1953 and 1989. The fluctuation of the number of tests was dependent on the research and development projects and activities of the laboratory of wood durability.

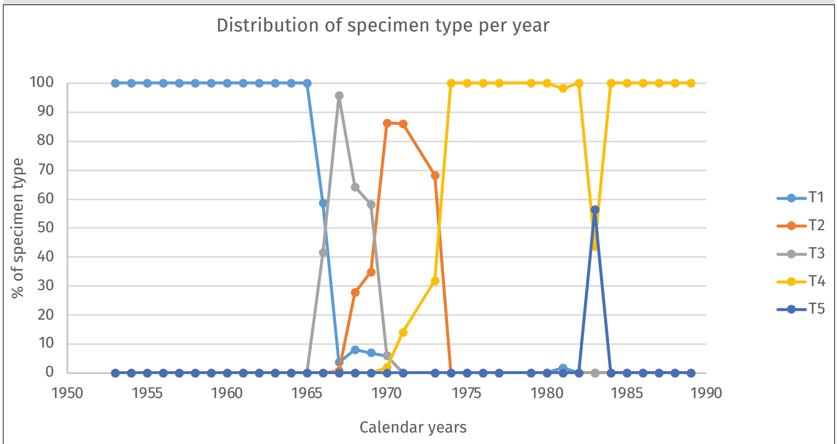

Figure 2.
Distribution in % of specimen type per calendar year.

with perforated metal caps closed by a wad of cotton wool and inoculated from stock cultures of the desired fungi (photo 1-1). Two weeks are needed in closed, dark rooms with even temperature and air humidity conditions (22 ± 2 °C and 70 ± 5% RH) for the fungi to cover the whole culture medium surface (photos 1-2). Z-shaped sterilised metal supports are placed upon the mycelium bed (photos 1-3) and sterilised wood blocks are placed upon the metal supports (photos 1-4) where they will be exposed to the mycelium during the test period (photos 1-5). The total test duration in the darkroom is usually 16 weeks (11% of the tests were carried out during 12 weeks).

Moisture control blocks are used to estimate the mean equilibrium moisture content (MC_s, in %) for the species in the standard condition (20 ± 2 °C, 65 ± 5% RH). If M_0 is the mass of the test block at the equilibrium moisture content, its theoretical initial anhydrous mass (M_i, in g) should be:

$$M_i = \frac{M_0}{(1 + MC_s)}$$

At the end of the 16 weeks of fungal exposure, samples were carefully cleaned of the mycelium remains on their surfaces and they were weighed at the final mass (M_f, in g). Then, all the samples were oven dried at 103 ± 2 °C until mass stabilisation in order to record their anhydrous mass (M_a, in g), allowing calculation of the final moisture content (MC_f, in %) of the wood samples (which should be over 25%), and the relative mass loss (ML, in %) due to the fungal attack that occurred during the test:

$$MC_f = \frac{(M_f - M_a)}{M_a}$$

$$ML = \frac{(M_i - M_a)}{M_a}$$

The same whole procedure is done at the same time with reference wood blocks of a not-durable species (scots pine sapwood or beech, usually), used as virulence control samples to check the efficiency of the tested fungi. For pine and beech virulence control samples, the required minimum median values of mass loss are 30% for brown rots and 20% for white rots.

Sample dimensions and wood zones

Most specimens came from trees with a reference in the CIRAD collection (Langbour et al. 2019) and were delivered by the carpenter's workshop to the wood preservation laboratory. Ten neighbouring specimens were used for each of the 9,842 tests. Five different geometries, all rectangular parallelepiped (T1 to T5) were used (table I). T1 type is the mini wood-block test used by Bravery (1978) and later by Deklerck et al. (2019).

Block type T1 was massively used between 1953 and 1965, while it was type T4 after 1975. Together, T1 and T4 types account for 84% of all the tests, and globally, 90% of all tests had a 16-week duration. Testing with a 12-week duration concerns massively T3 block type, while it represents only 1% for T1 and T4 types. Accordingly, the study of duration influence is not possible on these data. All results analysed in the paper are limited to 16-week durations on both T1 and T4 block types.

Heartwood (HW) and sapwood (SW) portions respectively represent 89% and 11% of all the tests. The two zones are analysed separately.

Fungal strains

A total of 28 fungal strains (FS) were used, but six of them accounted for 86% of the tests (table II).

The four fungal strains F1, F2, F4, and F6 together account for 77% of all tests, and they are very often used all four together. Analyses are done only for these four strains. In adding T1 + T4 block types tested against the 4 fungal strains (F1 + F2 + F4 + F6), this accounts for 68% of all the tests (6,677 tests). Those are the basis of further analysis.

Description of the database

The available data coming from the tests previously described and used for this present survey are divided into three data sheets and two comment sheets (Candelier et al. 2023). All these sheets are detailed below.

Decay test sheet

This gathers the results from the 9,842 tests in CTFT reference numerical order (472 tests have no N° CTFT) with the 14 following columns: Species, Country (the provenance of the tree), N° CTFT, Vernacular name, Year (of the test), Spec. type (dimension of the specimen tested), Duration (duration of the test), Nb FS (number of fungal strain used), FS (fungal strain used), Zone (heartwood or sapwood), Nb Spec. (number of specimens tested against the fungal strain), mean ML (mean mass loss), min ML (minimum mass loss), max ML (maximum mass loss).

Decay + Chemistry T1 HW sheet

This second sheet gathers the results for 182 species. It was built from the decay test sheet for the mass loss, using only heartwood specimen type T1 against the four standard fungal strains (F1, F2, F4, F6) and from the chemical data sheet (Gérard et al. 2019) for the chemical composition and density of the species common to both sheets. There are 15 columns: Family, Genus, Species, mean ML (mean value of mass losses for the 4 fungal strains), D*ML (product of the two values: density and mean mass loss for the species), mean Nb (mean number of trees tested against the 4 fungal strains), Nb trees (number of trees in the chemical test), AB ext (% extractive content in alcohol-benzene solution), W ext (% extractive content in hot water), Ash (% mineral content), Silica (% silica content), Tot (total result of chemical analyses in %), Lig rel (relative lignin content in %), Pento rel (relative pentosan content in %), Cell rel (relative cellulose content in %).

For lignin, pentosane, and cellulose content, relative means that the proportion is based on the extracted mass instead of the initial dry mass, to avoid low values due to very high levels of extractives that are not representative of the basic lignocellulosic matter.

Decay + Chemistry T4 HW sheet

This sheet gathers the results for 100 wood species. It was built just like the precedent sheet but using only heartwood specimen type T4.

Species T1 sheet

This sheet gathers the results for 219 species. It was built from the decay test sheet for the mass loss, using only heartwood specimen type T1 against the four standard fungal strains (F1, F2, F4, F6).

Table I.
Description of the different specimen geometries.

Type	Number	Length	Width	Height	Volume	Surface	Sur/Vol	ML	16 weeks
T1	3,559	30	10	5	1,500	1,000	0.67	22.60	99.8%
T2	507	50	14	5	3,500	2,040	0.58	20.93	95.5%
T3	943	50	14	14	9,800	3,192	0.33	19.21	1.1%
T4	4,722	50	25	15	18,750	4,750	0.25	18.10	98.7%
T5	111	50	17	17	14,450	3,978	0.28	22.39	100.0%

Length (in the longitudinal axis), Width and Height in mm, V olume in mm^3.
Surface: sum of the 6 face's areas in mm^2.
Sur/Vol: ratio between surface and volume in mm^{-1}.
ML: mean mass loss on all specimens from the same type (%).
16 weeks: proportion of tests during 16 weeks (the other tests duration is 12 weeks).

There are 18 columns: The first column concerns the Species T1 (all species for specimen type T1). Then, one block composed of the 4 following was done for each standard fungal strain (F_i = F_1, F_2, F_4 or F_6): Nb Fi (number of tests for fungal strain Fi), Mean (mean mass loss value for Fi), Min (minimum mass loss value for Fi), Max (maximum mass loss value for Fi). Finally, the last column is G mean (global mean mass loss for the 4 fungal strains F1, F2, F4 and F6).

Species T4 sheet

This sheet gathers the results for 151 species. It was built just like the precedent sheet, but using only heartwood specimen type T4.

Database and statistical methods

All the informative data and metadata about the collection have been recorded in digital files since 1980 (Gérard and Narboni 1996). In the open data file associated with this survey, the botanical names have been updated and mean density values have been added at the species level.

Table II.
Fungal strain (FS) used.

FS	Species	Type	Nb	%	ML
F1	*Pycnoporus sanguineus*	White rot	1,400	14.2	14.86
F2	*Lentinus squarrosulus*	White rot	1,849	18.8	21.08
F3	*Coriolopsis polysona*	White rot	825	8.4	22.80
F4	*Antrodia* sp.	Brown rot	2,169	22.0	26.90
F5	*Coniophora puteana*	Brown rot	506	5.1	7.40
F6	*Coriolus versicolor**	White rot	2,181	22.2	19.90
Total			**8,930**	**84.9**	**19.00**

Nb: total number of tests for the strain.
ML: mean mass loss for the strain (%).
* *Coriolus versicolor* is now known by its accepted scientific name *Trametes versicolor*.

Basic statistical analyses were performed using the XLSTAT 2020.5.1 software. The data description table includes the number of present and missing data, minimum, maximum, 1st quartile, median, 3rd quartile, and mean (with its standard deviation) values for each parameter, as well as the coefficient of variation (CV), skew (Pearson) and kurtosis (Pearson) of the distribution. A box plot is also given for each parameter. The box plot shows the quartiles (the band inside the box is the median). Whiskers plot the lowest data item still within the 1.5 IQR (interquartile range) of the lower quartile, and the highest data item is still within the 1.5 IQR of the upper quartile.

For the histogram presentation, the amplitude was chosen for each parameter to have a clear description of the data. The normality of the distribution was verified by Shapiro-Wilk tests. A Pearson-type correlation analysis was used for a normal distribution and a Spearman-type correlation analysis for a non-normal distribution.

Results and discussions

Influence of testing conditions

Two sample sizes (T1 and T4), two types of wood (HW and SW), and four fungal strains (F1, F2, F4, and F6) are considered for this survey. All of these parameters are presented in table III. The number and nature of the wood species tested under a given set of conditions are very different (few species are tested with both specimen dimensions). Moreover, there are sometimes rather large variations among species for the same set of conditions, and the number of trees per species and set of conditions is very low (most often only one tree).

The values in the Total column or heartwood (HW) lines are more reliable for comparisons. There are very significant differences between fungal strains, specimen dimension, and type of wood. At a mean, the mass loss for the smallest dimension (T1) is around 40% higher than for the T4 dimension. Sapwood loses around 45% more mass than heartwood.

Variability of results

Each test was performed on 10 specimens with the same position in the tree, and the mean, minimum, and

Table III.
Mean global results for standard tests.

Category		Total	F1	F2	F4	F6
16W T4 HW	Nb test	3,461	610	747	1,047	1,057
	Nb species		173	228	249	249
	ML	17.59	11.45	13.25	25.72	16.14
16W T4 SW	Nb test	685	109	161	217	198
	Nb species		68	87	106	107
	ML	25.47	21.57	20.43	32.23	24.31
16W T1 HW	Nb test	2,364	597	622	561	584
	Nb species		260	267	252	248
	ML	24.11	16.72	28.87	26.34	24.44
16W T1 SW	Nb test	167	43	44	43	37
	Nb species		24	25	24	22
	ML	34.62	25.10	38.43	36.53	38.93
T1/T4 HW	ML	1.37	1.46	2.18	1.02	1.51
T1/T4 SW	ML	1.36	1.16	1.88	1.13	1.60
SW/HW T1	ML	1.44	1.50	1.33	1.39	1.59
SW/HW T4	ML	1.45	1.88	1.54	1.25	1.51

FS: fungal strain (F1, F2, F4, F6) see Table 2.
Nb tests: total number of tests in the category.
Nb species: total number of species tested in the category.
mean ML: mean mass loss for the tests in the category (%).
16W T1 HW: test duration 16 weeks, with T1 specimen type (see Table 1), on heartwood.
16W T1 SW: test duration 16 weeks, with T1 specimen type, on sapwood.
16W T4 HW: test duration 16 weeks, with T4 specimen type (see Table 1), on heartwood.
16W T4 SW: test duration 16 weeks, with T4 specimen type, on sapwood.
T1/T4 HW: ratio between specimen type T1 and T4 mass loss for heartwood, general mean (first column), mean for a given fungal strain in the other columns.
T1/T4 SW: ratio between specimen type T1 and T4 mass loss for sapwood, general mean (first column), mean for a given fungal strain in the other columns.
SW/HW T1: ratio between specimen type sapwood and heartwood mass loss for specimen type T1, general mean (first column), mean for a given fungal strain in the other columns.
SW/HW T4: ratio between specimen type sapwood and heartwood mass loss for specimen type T4, general mean (first column), mean for a given fungal strain in the other columns.

Table IV.
Mean global results for standard tests.

Species	Nb tree	Mean ML (%)	CV tree (%)
Tectona grandis T4 SW	11	19.25	22.7
Tectona grandis T4 HW	11	6.67	46.6
Tectona grandis T1 SW	17	10.07	71.4
Aucoumea klaineana T1 HW	15	42.98	16.5
Triplochiton scleroxylon T1 HW	12	36.36	16.9
Cedrela odorata T4 HW	8	12.56	59.8
Shorea polysperma T4 FS4 HW	5	26.62	26.0
Shorea palosapis T4 FS4 HW	7	24.25	26.2
Shorea negrosensis T4 FS4 HW	6	30.45	8.3

Tx SW: mean values for Tx specimen type in sapwood.
Tx HW: mean values for Tx specimen type in heartwood.
T4 FS4 HW: mean values for T4 specimen type in heartwood tested with fungal strain FS4.
Nb tree: number of trees within the species.
Mean ML: mean value of the mean mass loss for all the tests in each tree.
CV tree: coefficient of variations of mean values.

maximum values of the mass loss for these 10 samples are given in the open data file (Candelier et al. 2023). The result is that the mean difference between maximum and minimum values amounts to 68% of the mean value, which means that there is a rather strong variability within decay tests themselves. This is the reason for testing 10 different specimens from the same position for each test.

There are 34 trees (same CTFT ID) where more than 5 different positions were tested inside the same tree using the same testing conditions: T4 specimen, FS4 fungal strain. The variability of mass loss values is measured by the standard deviation (figure 3). It appears that within-tree standard deviation values are much greater for trees with mass loss in the central range (mean ML between 15% and 30%). In comparison, there are few variations (small standard deviation for high mass loss) for the less durable (ML > 35%) and the most durable (ML < 5%) species.

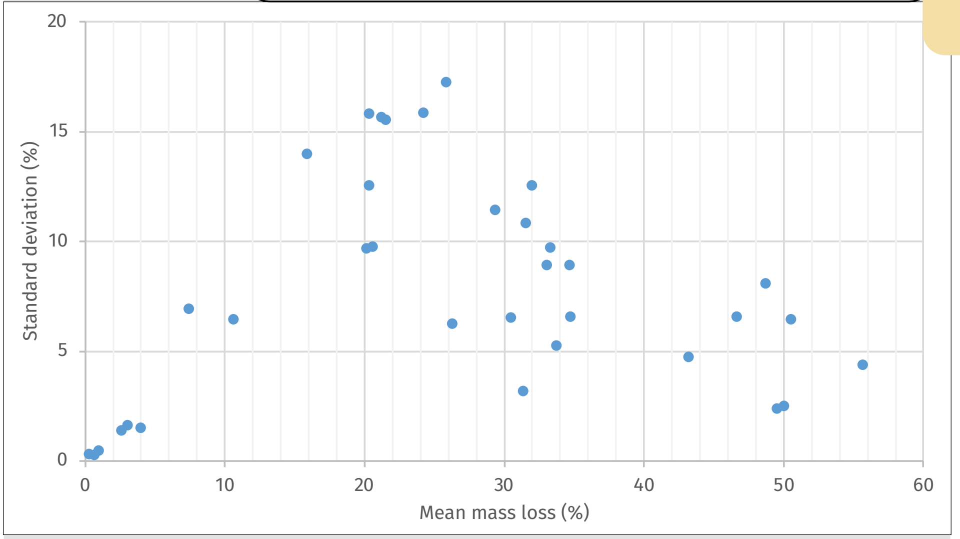

Figure 3.
Variability of mass loss within 34 trees having at least 5 tests. All specimens are T4 type and fungal strain FS4 is always used. In the vertical axis: standard deviation for the mass loss values within a tree. In the horizontal axis: mean mass loss for all tests in a tree.

For nine species, there are at least five different trees that were tested (table IV). For the less durable species (ML above 30%), variations between trees are rather low (CV below 20%), but they are quite high (CV near or above 50%) for the durable woods (ML below 15%).

This was described in the literature as the occurrence of far fewer durable trees within a durable species such as *Dycorinia guianensis*, *Tectona grandis,* or *Quercus petrea* (Guilley et al. 2004, Amusant et al. 2004, Moya and Berrogal 2010). Often, those trees are a minority and are characterised by low levels of extractives for this given species (Guilley et al. 2004). If these species are chosen for high-durability uses, it might be advisable to set up a sorting system based on a chemical test, such as near-infrared spectroscopy (Zahri et al. 2008), as is the case for mechanical sorting for structural use.

Difference between sapwood and heartwood

For the specimen dimension T4 (which is the standard now), there are 106 species with results against two different fungal strains, both on sapwood and heartwood. There are always very significant differences (at 0.1% level) between the 2 wood portions. Moreover, there is a very significant positive correlation between heartwood and sapwood mass losses (figure 4).

Table V gathers the results by class of global mean mass loss for the heartwood of the species. It appears in table V that globally, sapwood resistance to decay is higher for species with durable heartwood than for non-durable wood species, but the difference between sapwood and heartwood resistance is naturally much higher for species with durable heartwood.

Species influence

To have enough tests using the 4 most frequent fungal strains, it was decided to carry out two separate analyses on small specimens (T1 type) and big specimens (T4 type)

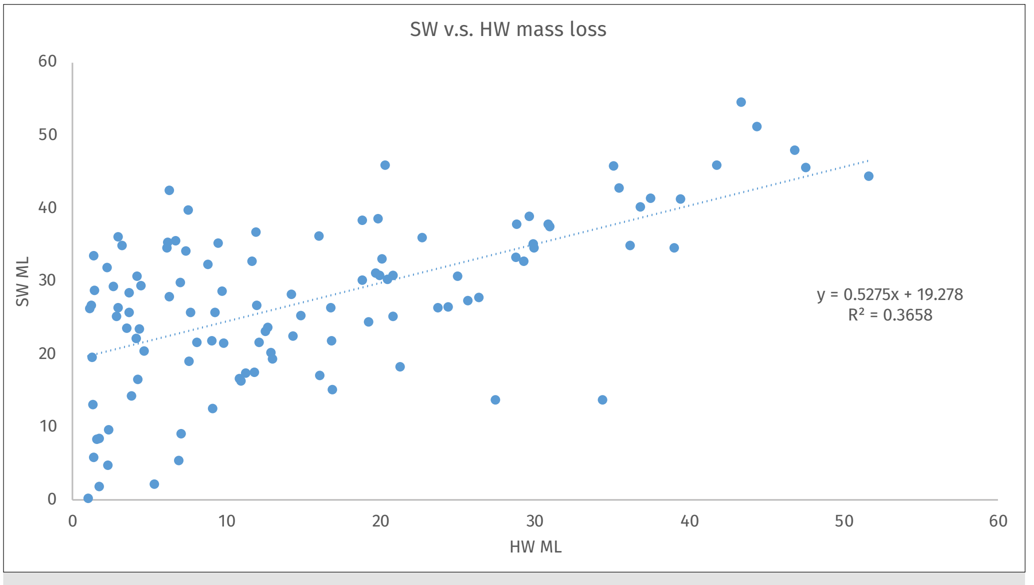

Figure 4.
Relationship between mean sapwood and heartwood mass loss for 106 species. In the vertical axis: SW ML represents the mean mass loss for sapwood against fungal strains F4 and F6. In the horizontal axis: HW ML represents the mean mass loss for sapwood against fungal strains F4 and F6.

and to use the species sharing the 4 fungal strains in each category: 219 species for type 1 specimens and 151 species for type 4 specimens. The global mean (G mean) value of the mass loss was calculated for each wood species as the mean value for the mass losses against the 4 fungal strains.

The distributions of values are very large (with coefficients of variation of 66% and 92% for T1 and T4, respectively) and not normal (figure 5, figure 6 and table VI).

With both T1 and T4 specimen types, the G mean has a very high correlation (using the Spearman correlation test) with the mean value of Mass loss from each fungal strain (tables VI and VII). In this sense, the G mean value could be used as a proxy to estimate the wood decay resistance according to the species.

Links with species' chemical composition

By examining the data on the chemical composition of wood (Gérard et al. 2019) for the same species (and usually the same trees), it was possible to find 182 species tested with type T1 specimens and 100 species tested with type T4 specimens. These two samplings allowed a reasonable statistical analysis to be carried out on the correlations between natural decay resistance and the chemical composition of wood.

The description of the data (tables VIII and IX) shows that the sampling of species covers a wide range of density and chemical composition. Moreover, the variability (CV) is very high for fungal mass loss, similar to the variability of extractive content but much higher than the variability in density or cell wall polymer proportion.

A very significant negative correlation between mass loss, density, AB extract, and relative lignin content (table X and XI) is always observed. When total mass loss (D*ML) is used instead of relative mass loss (mean ML), the correlation is weaker with density (though still highly significant), but remains very similar for AB extract or lignin content.

Density, extractives, and lignin are always described as the main factors explaining wood resistance to decay (Sundararaj 2015, Scheffer and Morrell 1998, Fougerousse 1960, Deklerck et al. 2019, Stirling et al. 2017). The role of density is often discussed, as there are many counter-examples (Akhter et al. 2003, Fougerousse 1960). According to Willeitner and Peek (1997), "If test results are based on mass loss as a percent of the initial weight this will be favourable for high-density timber, as demonstrated in a small test". Moreover, according to Willeitner (1984), "the same absolute mass loss of maybe 6 g will be 50% for a specimen of 12 g mass and only 30% in case of an 18 g specimen". For this reason, the value D*ML was used because it is proportional to absolute mass loss while ML is a relative mass loss (note that this is still a Spearman correlation test). The results highlight that the correlation with density is lower for D*ML, but it is still very significant (tables X and XI), showing that this argument is not sufficient. On the contrary, the level of correlation is the same between both extractives

Table V.
Comparison between mean mass loss (ML, in %) from heartwood and sapwood for 106 species.

HW Mean	Nb	F4 HW mean ML	F6 HW mean ML	HW mean ML	F4 SW mean ML	F6 SW mean ML	SW mean ML	SW-HW F4	SW-HW F6	SW-HW Mean
< 5	28	2.07	3.16	2.62	23.81	17.81	20.81	21.74	14.64	18.19
[5 ; 10[	20	8.08	7.20	7.64	28.56	22.97	25.77	20.48	15.77	18.12
[10 ; 15[	14	16.16	8.33	12.25	25.39	20.78	23.08	9.23	12.44	10.84
[15 ; 20[	11	23.75	12.32	18.04	34.85	21.55	28.20	11.10	9.22	10.16
[20 ; 25[	9	25.43	17.69	21.56	34.29	26.25	30.27	8.86	8.56	8.71
[25 ; 30[	9	33.86	22.90	23.38	33.89	28.67	31.28	0.03	5.76	2.90
> 30	15	47.81	31.02	39.42	47.75	34.78	41.26	-0.06	3.76	1.85

HW mean: class of global mean heartwood values.
Nb: number of common species in the class.
F4 HW: tests of the species heartwood against fungal strain 4.
F6 HW: tests of the species heartwood against fungal strain 6.
F4 SW: tests of the species sapwood against fungal strain 4.
F6 SW: tests of the species sapwood against fungal strain 6.
HW: mean of the tests against F4 and F6 for heartwood (global mean).
SW: mean of the tests against F4 and F6 for sapwood (global mean).
SW-HW: difference of mean mass loss between sapwood and heartwood.
F4, F6: test against fungal strain F4 and F6 respectively.
Mean ML: mean mass loss for the tests in the category (%).

Table VI.
Coefficient of correlation for mass loss between fungal strains for T1 specimens.

Spec. T1	Mean F1	Mean F2	Mean F4	Mean F6	G Mean
Mean F1	**1**	**0.649**	**0.608**	**0.764**	**0.810**
Mean F2	**0.649**	**1**	**0.713**	**0.735**	**0.906**
Mean F4	**0.608**	**0.713**	**1**	**0.671**	**0.872**
Mean F6	**0.764**	**0.735**	**0.971**	**1**	**0.879**
G Mean	**0.810**	**0.906**	**0.872**	**0.879**	**1**

Spec. T1: species tested with specimen type T1
Mean Fi: mean value of mass loss for the species using fungal strain Fi
G mean: global mean value for the 4 fungal strains for the species
Bold characters: significant value at level 0.1%

(AB extract) and lignin content and both ML and D*ML. All these results show that it is difficult to find a direct causality between high density and high resistance to decay when looking at the action of fungi on wood, while there are reasons for inhibiting the effect of extractives and lignin on fungal activity. There is probably a synergetic effect of both high-density and highly efficient extractives in tropical woods that confers on the wood a good natural durability against wood-destroying fungi (Scheffer and Morrell 1998).

Key findings

The great number of decay tests performed in the same conditions for at least two different specimen dimensions and four fungal stains confirms the findings from Willeitner and Peek (1997). There is a very large variability in resistance to decay, and results are strongly dependent on specimen type and fungal strain (besides test duration).

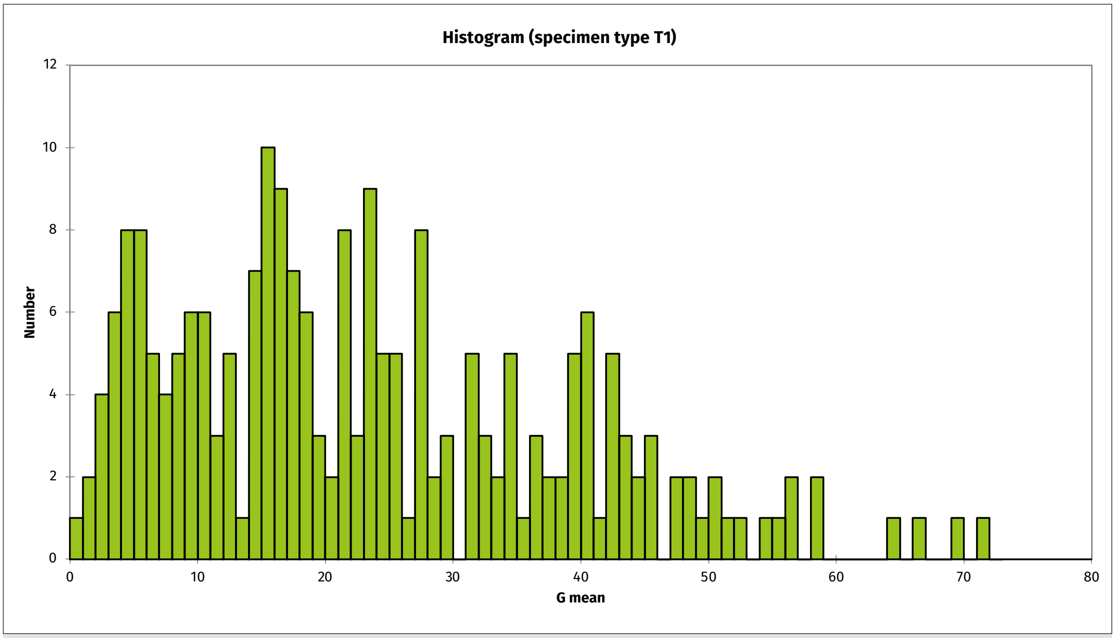

Figure 5.
Distribution of mean mass loss per species for T1 specimens.

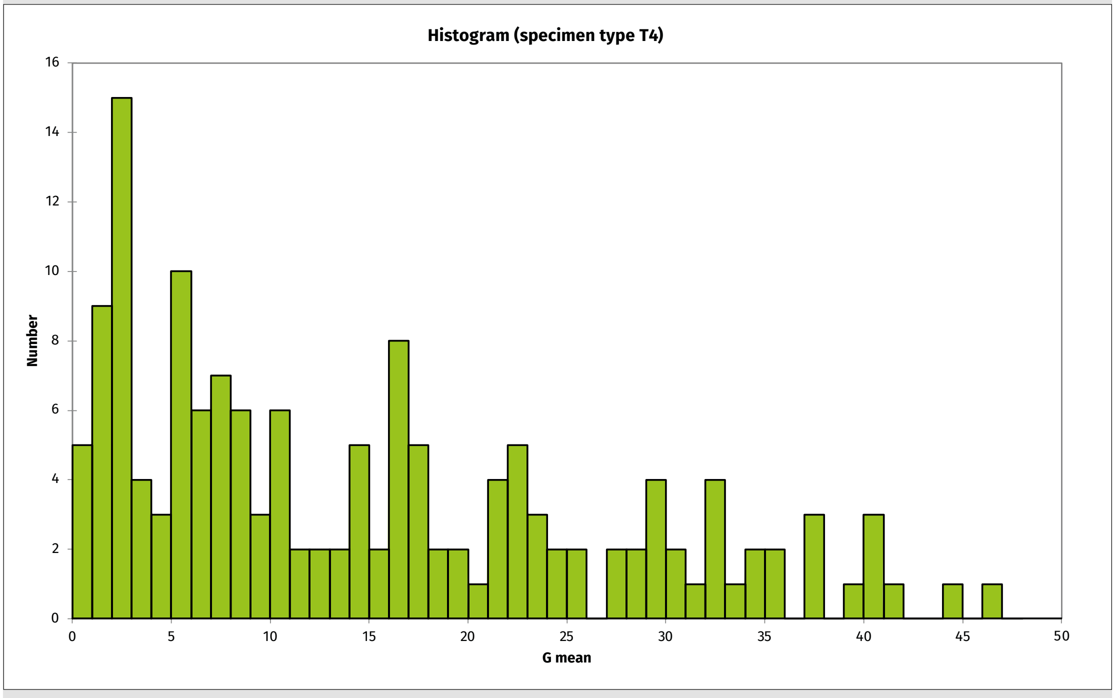

Figure 6.
Distribution of mean mass loss per species for T4 specimens.

The two specimen dimensions used are very different in volume and ratio surface/volume (table I), and this should explain the higher relative mass loss values (+40%) for the smaller specimen compared to those of bigger sample sizes, both experiencing the same fungal exposure duration (Bravery 1978).

Using the mean mass loss for 4 different fungal strains allows for a more robust description of each wood species. When looking at the ranking of species by mean mass loss for each specimen dimension (T1 and T4), the result is similar to the results from the scientific literature (Scheffer and Morrell 1998) concerning durable versus non-durable wood species.

There were enough species combining sapwood and heartwood specimens with the same set of conditions to have a look at the differences between sapwood and heartwood. For the same wood species, heartwood is more resistant to decay (+45%) than sapwood. In addition, sapwood durability is globally higher for a wood species with a durable heartwood compared to sapwood from a wood species with a low durable heartwood. The difference in fungal resistance between heartwood and sapwood for a species is also higher for highly resistant heartwood. There is a very large diversity of situations in the durable wood species, sometimes sapwood is fairly resistant, and sometimes it has a very low resistance towards fungi.

In this collection of data, lignin content seems to be as influential as extractives, but only specific extractives prove to be very efficient against fungal decay (Neya et al. 2004). The problem with the value of extractive content from this open data file is that their chemical compositions are not known. In this sense, some of these wood species could contain extractives with anti-fungal and/or insecticide activities, and some wood species could be resistant to insects but not to fungi (Fougerousse 1960).

The publication in open source (Candelier et al. 2023) of these old data is an opportunity to enhance the knowledge of wood species concerning their decay resistance, by collecting other numerical data to perform some meta-analysis with better statistical robustness. Ranking of the species (either in T1 or T4 block types) by the mean value of mass loss for the four main fungal strains, together with their basic chemical compositions, can be used for further investigations on the lignin proportion of monomers on one side and the chemical description of extractives (and maybe some mineral compounds) on the other side to better understand the decay resistance of wood, together with the discovery of active molecules towards fungi metabolism.

Table VII.
Coefficient of correlation for mass loss between fungal strains for T4 specimens.

Spec. T1	Mean F1	Mean F2	Mean F4	Mean F6	G Mean
Mean F1	**1**	**0.892**	**0.764**	**0.871**	**0.901**
Mean F2	**0.892**	**1**	**0.753**	**0.870**	**0.942**
Mean F4	**0.764**	**0.753**	**1**	**0.812**	**0.882**
Mean F6	**0.871**	**0.870**	**0.812**	**1**	**0.929**
G Mean	**0.901**	**0.942**	**0.882**	**0.929**	**1**

Spec. T4: species tested with specimen type T4.
Mean Fi: mean value of mass loss for the species using fungal strain Fi.
G mean: global mean value for the 4 fungal strains for the species.
Bold characters: significant value at level 0.1%.

Table VIII.
Description of data for specimen type T1 (182 species).

T1 (182 species)	Min	Max	Mean	CV (%)
Mean ML	0.0	71.9	23.4	65.8
D * ML	0.0	409	146	55.4
D	252	1,26	703	27.0
AB ext	0.60	21.20	4.84	78.6
W ext	0.20	12.13	3.00	60.7
Ash	0.10	4.53	0.97	71.8
Tot	87	101	96	2.2
Lig rel	22.8	43.4	32.7	12.0
Pento rel	6.3	26.9	17.2	18.7
Cell rel	38.1	55.0	45.7	6.9

Mean ML: mean value of mass losses for the 4 fungal strains (%).
D*ML: product of the two values: density and mean mass loss for the species.
D: density for the species, in kg/m3.
AB ext: % extractive content in alcohol-benzene solution.
W ext: % extractive content in hot water.
Ash: % mineral content.
Silica: % silica content.
Tot: total result of chemical analyses in %.
Lig rel: relative lignin content in %.
Pento rel: relative pentosan content in %.
Cell rel: relative cellulose content in %.

Table IX.
Description of data for specimen type T4 (100 species).

T4 (100 species)	Min	Max	Mean	CV (%)
Mean ML	0.3	46.9	15.6	77.5
D * ML	2	291	99	70.6
D	240	1210	716	28.4
AB ext	0.20	20.06	5.09	69.5
W ext	0.90	8.50	2.94	48.9
Ash	0.02	3.16	0.92	75.5
Tot	90.7	101.5	96.6	2.2
Lig rel	19.1	45.8	32.4	14.3
Pento rel	6.0	25.2	16.4	20.6
Cell rel	36.3	59.9	47.5	9.4

Mean ML: mean value of mass losses for the 4 fungal strains (%).
D*ML: product of the two values: density and mean mass loss for the species.
D: density for the species, in kg/m3.
AB ext: % extractive content in alcohol-benzene solution.
W ext: % extractive content in hot water.
Ash: % mineral content.
Silica: % silica content.
Tot: total result of chemical analyses in %.
Lig rel: relative lignin content in %.
Pento rel: relative pentosan content in %.
Cell rel: relative cellulose content in %.

Table X.
Correlation table for mass loss, chemical composition for T1 (182 species).

T1 (182 species)	Mean ML	D * ML	D	AB ext	W ext	Ash	Tot	Lig rel	Pento rel	Cell rel
Mean ML	**1**	**0.913**	**-0.631**	**-0.477**	-0.210	0.143	**-0.334**	**-0.502**	0.189	0.235
D * ML	**0.913**	**1**	**-0.316**	**-0.525**	-0.218	0.125	**-0.309**	**-0.458**	0.178	0.201
D	**-0.631**	**-0.316**	**1**	0.081	0.058	-0.133	0.170	0.338	-0.160	-0.184
AB ext	**-0.477**	**-0.525**	0.081	**1**	0.226	-0.111	**0.257**	0.172	0.134	-0.175
W ext	-0.210	-0.218	0.058	0.226	**1**	0.239	0.199	0.077	0.160	-0.127
Ash	0.143	0.125	-0.133	-0.111	0.239	**1**	0.079	-0.053	0.196	-0.063
Tot	**-0.334**	**0.309**	0.170	**0.257**	0.199	0.079	**1**	0.541	-0.005	0.003
Lig rel	**-0.502**	**-0.458**	**0.338**	0.172	0.077	-0.053	**0.541**	**1**	**-0.423**	**-0.443**
Pento rel	0.189	0.178	-0.160	0.134	0.160	0.196	-0.005	**-0.423**	**1**	**-0.372**
Cell rel	0.235	0.201	-0.184	-0.175	-0.127	-0.063	0.003	**-0.443**	**-0.372**	**1**

Mean ML: mean value of mass losses for the 4 fungal strains (%).
D*ML: Product of the two values: density and mean mass loss for the species.
D: density for the species, in kg/m3.
AB ext: % extractive content in alcohol-benzene solution.
W ext: % extractive content in hot water.
Ash: % mineral content.
Silica: % silica content.
Tot: total result of chemical analyses in %.
Lig rel: relative lignin content in %.
Pento rel: relative pentosan content in %.
Cell rel: relative cellulose content in %.
Bold characters: significant value at level 0.1%.

Table XI.
Correlation table for mass loss, chemical composition for T4 (100 species).

T4 (100 species)	Mean ML	D * ML	D	AB ext	W ext	Ash	Tot	Lig rel	Pento rel	Cell rel
Mean ML	**1**	**0.947**	**-0.574**	**-0.493**	0.101	**0.479**	-0.203	**-0.343**	0.245	0.122
D * ML	**0.947**	**1**	-0.324	**-0.481**	0.157	**0.449**	-0.265	-0.325	0.295	0.029
D	**-0.574**	-0.324	**1**	0.273	0.061	-0.313	-0.125	0.148	0.049	-0.301
AB ext	**-0.493**	**-0.481**	0.273	**1**	-0.018	-0.171	0.273	0.240	0.078	-0.214
W ext	0.101	0.157	0.061	-0.018	**1**	0.161	0.011	-0.055	0.292	-0.202
Ash	**0.479**	**0.449**	-0.313	-0.171	0.161	**1**	-0.196	-0.262	**0.341**	-0.083
Tot	-0.203	-0.265	-0.125	0.273	0.011	-0.196	**1**	0.309	-0.200	0.260
Lig rel	**-0.343**	-0.325	0.148	0.240	-0.055	-0.262	0.309	**1**	**-0.462**	**-0.535**
Pento rel	0.245	0.295	0.049	0.078	0.292	**0.341**	-0.200	**-0.462**	**1**	-0.319
Cell rel	0.122	0.029	-0.301	-0.214	-0.202	-0.083	0.260	**-0.535**	-0.319	**1**

Mean ML: mean value of mass losses for the 4 fungal strains (%).
D*ML: Product of the two values: density and mean mass loss for the species.
D: density for the species, in kg/m3.
AB ext: % extractive content in alcohol-benzene solution.
W ext: % extractive content in hot water.
Ash: % mineral content.
Silica: % silica content.
Tot: total result of chemical analyses in %.
Lig rel: relative lignin content in %.
Pento rel: relative pentosan content in %.
Cell rel: relative cellulose content in %.
Bold characters: significant value at level 0.1%..

Conclusion

A database of decay resistance related to density, chemical composition, and zones (heartwood and sapwood) of wood has been built from 9,842 tests carried out on 500 tropical wood species in CIRAD, since 1953. All these tests were not carried out with the same protocol nor under identical conditions. Five different sample sizes, six fungal strains, and heartwood and sapwood fractions have been explored, giving significantly different results. However, most of the tests used the same fungal exposure duration (i.e., 16 weeks), and the mean mass loss due to the four main fungal strains is a good predictor of the wood decay resistance. In addition, the results confirm that there is probably a synergetic effect of both high-density and highly efficient extractives in tropical woods that confers on the wood a good natural durability against wood-destroying fungi. The publication of these old data in open source is an opportunity to enhance the knowledge of wood species concerning their decay resistance, by collecting other numerical data to perform some meta-analysis with better statistical performance. However, it's important to point out that the results coming from this database concern only 4 strains of wood-destroying fungi, which, even if carefully selected, do not fully reflect the great fungal diversity of natural conditions, which often bring surprises when it comes to natural durability.

In general, standards tend to rank wood's natural durability in order of worst-case performance. However, very poor tests are often the exception in databases, and better classification using high-throughput tools such as those proposed (NIRS) could enable better optimisation/pricing of natural durability, which is by far one of the most important in the current use of wood.

In the same way, additional chemical composition analyses of extractive compounds could be very interesting to be input within these data sheets, to better understand the decay resistance of wood together with the discovery of active molecules towards fungi metabolism. Finally, such analyses could also allow the identification of some interesting wood species for their resistance towards insects.

Funding and acknowledgements:
The constitution of the database, the machining of the samples, and the decay test were done with CIRAD's funds, as was the recruitment, and finally, we benefited from the voluntary work of Professor B. Thibaut, CNRS director emeritus.

Access to data:
Data are freely available and have been uploaded to the CIRAD dataverse:
Candelier K., Thévenon M. F., Gérard J., Thibaut B., 2023. CIRAD wood resistance to decay database. CIRAD Dataverse. https://doi.org/10.18167/DVN1/ZAHGCF

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Candelier et al. – Author's contributions

Contributor role	Contributor names
Conceptualization	B. Thibaut, J. Gérard
Data Curation	J. Gérard, M.-F. Thévenon, K. Candelier
Formal Analysis	B. Thibaut
Visualization	B. Thibaut, M.-F. Thévenon, K. Candelier
Writing – Original Draft Preparation	B. Thibaut
Writing – Review & Editing	B. Thibaut, K. Candelier, J. Gérard, M.-F. Thévenon

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INTERNATIONAL CONFERENCE ON TROPICAL WOOD

ADVANCING THE SUSTAINABLE USE OF TROPICAL FORESTS

26TH – 28TH AUGUST 2024, ANTANANARIVO, MADAGASCAR

Tropical regions are renowned for the diversity and richness of their forests, which are sources of abundant resources, particularly wood. Tropical forests host a large diversity of wood and timber species. The large species diversity parallels a large variation in properties, such as color, density, hardness, and mechanical stress, offering various opportunities for use. Furthermore, its abundance in tropical regions facilitates accessibility to both urban and rural populations. Wood has long served as a primary material for construction and cooking fuel in tropical countries. However, traditional uses remain prevalent in timber harvesting and processing industries, catering to domestic and global markets, and illegal logging and irrational practices threaten the sustainability of the market.
Extensive reliance on wood leads to high deforestation and illegal logging, which is a major threat to tropical forests.

Therefore, developing and propagating practical research is fundamental to harnessing technological advancements and promoting sustainable utilization of tropical forest resources. The primary objective of this conference is to foster the exchange of knowledge and spotlight exemplary practices that align productive utilization with the sustainability of tropical forest resources. The aim is to inspire further research and development that promotes harmonious coexistence between meeting human needs and preserving these precious ecosystems.

Five themes will be addressed at this conference:

1. Tropical wood identification for sustainable supply chains of forest products.
2. Innovations in wood usage in construction across tropical countries.
3. Wood energy in the tropical countries.
4. Utilization of tropical wood in cultural artefacts.
5. Tropical non-timber forest products (NFTPs).

The conference is scheduled to take place from the 26th to the 28th of August 2024 in Antananarivo, the Capital of Madagascar. It will include invited keynotes, voluntary papers, round-table discussions, and field visits.
All presentations will be held live and on-site. The field visit will be organized in Mandraka Community forest, approximately 60 km from the capital. The language of the conference and its publications will be English.

Contact:
Tahiana Ramananantoandro, e-mail: tahiana.ramananantoandro@ens.esb-campus.fr

To get more information:
https://tropicalwood.sciencesconf.org/

Bois et Forêts des Tropiques – ISSN : L-0006-579X
Volume 358 – 4e trimestre – décembre 2023 – p. 67-72
DESCRIPTIF TECHNIQUE D'ESSENCE TROPICALE

Karri – *Eucalyptus diversicolor* F. Muell.

Extrait de l'*Atlas des bois tropicaux – Caractéristiques technologiques et utilisations*
J. Gérard (coord.), D. Guibal (au.), J.-C. Cerre (au.), S. Paradis (au.), et 40 auteurs, 2016. Éditions Quæ, 1 000 p.
https://www.quae.com/produit/1408/9782759225521/atlas-des-bois-tropicaux
Accès à la notice d'information générale :
https://doi.org/10.19182/bft2021.347.a36353

Faux quartier.
Photo D. Guibal, Cirad.

Quartier.
Photo D. Guibal, Cirad.

Famille. Myrtaceae.
Nom botanique. *Eucalyptus diversicolor* F. Muell.
Continent. Asie, Océanie.
CITES (Convention de Washington, 2016).
Pas de restriction commerciale.
Notes. Le Karri commercialisé actuellement n'est plus prélevé dans les forêts primaires. Il provient uniquement de forêts secondaires (Australie) ou des plantations (particulièrement d'Afrique du Sud).

Description de la grume

Diamètre. De 80 à 200 cm.
Épaisseur de l'aubier. De 3 à 6 cm.
Flottabilité. Non flottable.
Conservation en forêt. Bonne.

Description du bois

Couleur référence. Brun rosé.
Aubier. Bien distinct.
Grain. Moyen.
Fil. Droit ou contrefil.
Contrefil. Léger.
Notes. La fourchette de diamètre mentionnée correspond à des bois issus des forêts naturelles. Les bois provenant des forêts secondaires et des plantations ont des diamètres inférieurs.

Propriétés physiques et mécaniques

Propriété	Valeur moyenne
Densité[1]	0,90
Dureté Monnin[1]	7,3
Coefficient de retrait volumique	0,67 % par %
Retrait tangentiel total (Rt)	11,2 %
Retrait radial total (Rr)	7,6 %
Ratio Rt/Rr	1,5
Point de saturation des fibres	28 %
Conductivité thermique (λ)	0,29 W/(m.K)
Pouvoir calorifique inférieur	.
Contrainte de rupture en compression[1]	71 MPa
Contrainte de rupture en flexion statique[1]	119 MPa
Module d'élasticité longitudinal[1]	23 300 MPa

[1] À 12 % d'humidité, avec 1 MPa = 1 N/mm².

Notes. Bois dur. Les propriétés physiques et mécaniques des bois provenant des plantations varient fortement en fonction de l'âge des arbres et de leurs conditions de croissance.

Bois et Forêts des Tropiques – ISSN: L-0006-579X
Volume 358 – 4th quarter – December 2023 – p. 67-72

Durabilité naturelle et imprégnabilité du bois
Résistance aux champignons. Classe 2 – durable.
Résistance aux insectes de bois sec. Classe D – durable (aubier distinct, risque limité à l'aubier).
Résistance aux termites. Classe S – sensible.
Imprégnabilité. Classe 4 – non imprégnable.
Classe d'emploi couverte par la durabilité naturelle. Classe 3 - hors contact du sol, à l'extérieur.

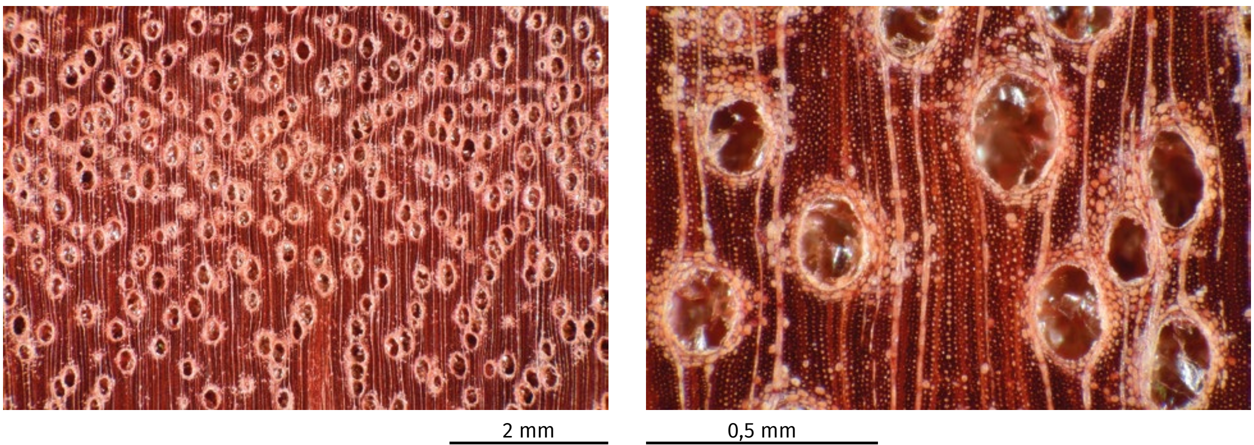
Notes. Cette essence est mentionnée dans la norme NF EN 350. La durée de performance peut être modifiée par les conditions d'utilisation (telle que décrite par la norme NF EN 335 de mai 2013).

Traitement de préservation
Contre les attaques d'insectes de bois sec. Ce bois ne nécessite pas de traitement de préservation.
En cas d'humidification temporaire. Ce bois ne nécessite pas de traitement de préservation.
En cas d'humidification permanente. L'utilisation de ce bois n'est pas conseillée.

Séchage
Vitesse de séchage. Lente.
Risque de déformation. Élevé.
Risque de cémentation. Pas de risque particulier connu.
Risque de fentes. Élevé.
Risque de collapse. Oui.
Programme de séchage proposé. Programme n°7 (voir note explicative).

Sciage et usinage
Effet désaffûtant. Assez important.
Denture pour le sciage. Denture stellitée.
Outils d'usinage. Au carbure de tungstène.
Aptitude au déroulage. Non recommandé ou sans intérêt.
Aptitude au tranchage. Non recommandé ou sans intérêt.

Sections transversales *Eucalyptus diversicolor.*
Photo J.-C. Cerre.



Assemblage

Clouage/vissage. Bonne tenue, avant-trous nécessaires.

Notes. Bois dense : la mise en oeuvre du collage doit particulièrement respecter les règles de l'art et les préconisations indiquées pour la colle utilisée.

Classements commerciaux

Classement d'aspect des produits sciés.
Selon les règles de classement MGR (2009).
Classements possibles coursons de chevrons : choix I, choix II, choix III.
Classement visuel de structure.
Conformément à la norme européenne EN 1912 (2012) associée aux normes nationales correspondantes (voir note explicative), la classe mécanique D50 peut être attribuée par classement visuel.

Réaction au feu

Classement conventionnel français.
Épaisseur > 14 mm : M3 (moyennement inflammable).
Épaisseur < 14 mm : M4 (facilement inflammable).
Classement selon euroclasses. D-s2, d0.
Ce classement par défaut concerne les bois massifs répondant aux exigences de la norme NF EN 14081-1 (avril 2016) : bois de structure utilisés en parois verticales et plafonds, classés, de densité moyenne minimale 0,35 et d'épaisseur minimale 22 mm.

Principales utilisations

Charpente lourde.
Ébénisterie (meuble de luxe).
Lambris.
Lamellé-collé.
Moulure.
Parquet.
Escalier d'intérieur.
Fond de véhicule ou de conteneur.
Parquet lourd ou industriel.
Pont (partie non en contact avec le sol ou l'eau).
Revêtement extérieur.

Principales appellations vernaculaires

Pays	Appellation
Australie	Karri

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Karri – *Eucalyptus diversicolor* F. Muell.

From Tropical timber atlas – Technological characteristics and uses.
J. Gérard (coord.), D. Guibal (au.), J.-C. Cerre (au.), S. Paradis (au.), and 40 authors, 2016. Publisher Éditions Quæ, 1000 p.
https://www.quae.com/produit/1477/9782759227716/tropical-timber-atlas
Access to the general information leaflet:
https://doi.org/10.19182/bft2021.347.a36353

Half-quarter sawn.
Photo D. Guibal, Cirad.

Quarter sawn.
Photo D. Guibal, Cirad.

Family. Myrtaceae.
Botanical name. *Eucalyptus diversicolor* F. Muell.
Continent. Asia, Oceania.
CITES (Washington Convention of 2017). No trade restrictions.
Notes. Karri commercialised today no longer comes from primary forests. It only comes from regrowth forests (Australia) or plantations (South Africa, especially).

Log description

Diameter. 80 to 200 cm.
Thickness of sapwood. 3 to 6 cm.
Buoyancy. Does not float.
Log conservation. Good.

Wood description

Reference colour. Pinkish brown.
Sapwood. Clearly demarcated.
Texture. Medium.
Grain. Straight or interlocked.
Interlocked grain. Slight.
Notes. The range of mentioned diameters corresponds to wood from natural forests. Woods from secondary forests and plantations are smaller in diameter.

Physical and mechanical properties

Property	Mean value
Density(1)	0.90
Monnin hardness(1)	7.3
Coefficient of volumetric shrinkage	0.67% per %
Total tangential shrinkage (Ts)	11.2%
Total radial shrinkage (Rs)	7.6%
T/R anisotropy ratio	1.5
Fibre saturation point	28%
Thermal conductivity (λ)	0.29 W/(m.K)
Lower heating value	.
Crushing strength(1)	71 MPa
Static bending strength(1)	119 MPa
Longitudinal modulus of elasticity(1)	23,300 MPa

(1) At 12% moisture content, with 1 MPa = 1 N/mm².

Notes. Hard wood. Physical and mechanical properties of Karri vary greatly according to trees age and growth conditions.

Natural durability and treatability

Resistance to decay. Class 2 – durable.
Resistance to dry wood borers. Class D – durable (sapwood demarcated, risk limited to sapwood).
Resistance to termites. Class S – susceptible.
Treatability. Class 4 – non-treatable.
Use class covered by natural durability. Class 3 – not in ground contact, outside.

Notes. This species is listed in the NF EN 350 standard. According to the European standard NF EN 335 of May 2013, performance length might be modified by conditions in which it is used.

Preservation treatment

Against dry wood borer attacks. This wood does not require any preservation treatment.
In case of temporary humidification. This wood does not require any preservation treatment.
In case of permanent humidification. Use of this wood is not recommended.

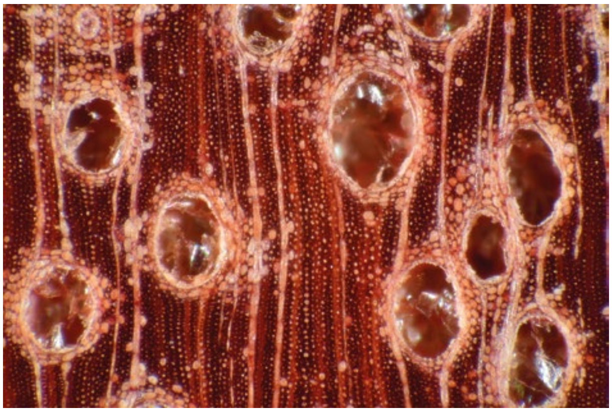
Drying

Drying rate. Slow.
Risk of distortion. Hight risk.
Risk of case hardening. No known specific risk.
Risk of checking. Hight risk.
Risk of collapse. Yes.
Suggested drying schedule. Schedule #7 (see explanatory note).

Sawing and machining

Blunting effect. Fairly high.
Tooth for sawing. Stellite-tipped.
Machining tools. Tungsten carbide.
Suitability for peeling. Not recommended or without interest.
Suitability for slicing. Not recommended or without interest.

Cross sections of *Eucalyptus diversicolor.*
Photo J.-C. Cerre.



Assembling

Nailing/screwing. Good but pre-boring necessary.

Notes. High specific gravity: important that gluing be performed in compliance with the code of practice and instructions for the glue used.

Commercial grading

Sawn timber appearance grading.
According to MGR grading rules (2009).
Possible grading: Prime, Select, Standard, Sound, Serviceable, Utility.

Visual structure grading.
According to European standard EN 1912 (2012) and associated national standards (see explanatory note), strength class D50 can be provided by visual grading.

Fire safety

Conventional French grading.
Thickness > 14 mm: M3 (moderately flammable).
Thickness < 14 mm: M4 (readily flammable).

Euroclass grading. D-s2, d0.
Default grading for solid wood that meets requirements of European standard NF EN 14081-1 (April 2016): structural graded timber in vertical uses and ceilings with minimal mean density of 0.35 and minimal thickness of 22 mm.

Main end uses

Heavy carpentry.
Cabinetry (high-end furniture).
Stairs (inside).
Vehicle or container flooring.
Industrial or heavy flooring.
Bridges (parts not in contact with water or ground).
Panelling.
Glued Laminated.
Moulding.
Flooring.
Exterior panelling.

Common names

Country	Local name
Australia	Karri

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RÉSUMÉ DE THÈSE / ACADEMIC THESIS ABSTRACT / RESUMEN DE TESIS ACADÉMICA

Le cryptoméria de La Réunion (*Cryptomeria japonica*) : durabilité naturelle face aux champignons basidiomycètes et aux termites, et apports de la spectroscopie proche infrarouge dans la prédiction de ses caractéristiques

Jérôme Vuillemin

RÉSUMÉ

Le cryptoméria (*Cryptomeria japonica*) est la seule essence de bois locale exploitable dans la construction à La Réunion. Cependant, sa durabilité variable face aux champignons basidiomycètes et aux termites constitue un frein au déploiement de son utilisation locale, où les conditions climatiques sont particulièrement favorables à la dégradation des matériaux biosourcés.

Cette thèse a consisté à déterminer avec précision la durabilité naturelle de cette essence face à deux espèces de champignons ubiquistes basidiomycètes (*Rhodonia placenta* et *Coniophora puteana*) et deux espèces de termites (*Coptotermes gestroi* de La Réunion et *Reticulitermes flavipes* de France continentale), en réalisant un très large échantillonnage. À titre comparatif, du pin sylvestre (faiblement durable), du Red cedar (durable), ainsi que des bardages en cryptoméria exposés à La Réunion depuis 7 ans ont été testés dans les mêmes conditions, délavés ou non, et soumis aux organismes lignivores selon les protocoles normalisés européens en vigueur. En complément, la spectroscopie proche infra-rouge, couplée à la chimiométrie, est utilisée afin de prédire la durabilité face aux champignons basidiomycètes.

Les résultats obtenus confirment la sensibilité du cryptoméria vis à vis des termites et attestent d'une très forte variabilité de la durabilité du cryptoméria face aux champignons. Les dispositions prévues dans la norme EN 350 (2016) ne permettent pas de classer cette essence car les valeurs de perte de masse (due à la dégradation des champignons) se répartissent dans les 5 classes de durabilité allant de « très durable » à « non durable ».

Le délavage et le vieillissement naturel permettent de mieux appréhender la performance du cryptoméria et de le classer « faiblement durable à non durable ». Le délavage n'a pas d'influence sur les performances du Red cedar et du pin sylvestre, lesquels restent classés « durable » et « faiblement durable » respectivement.

La spectroscopie proche infra-rouge est finalement un outil performant pour la prédiction de la durabilité naturelle de ces essences face aux champignons. À l'aide du modèle robuste développé, cet outil prédictif contribuera à une utilisation optimale du cryptoméria en permettant une évaluation non-destructive de la durabilité de ce bois dans le but d'assurer une performance optimale, en particulier en zone ultramarine tropicale.

Mots-clés : *Cryptomeria japonica*, cryptoméria, durabilité naturelle, champignons, termites, spectroscopie proche infra-rouge, modèle prédictif, performance du bois.

Cryptomeria japonica from Reunion Island: natural durability against basidiomycete fungi and termites, and contributions of near infrared spectroscopy to the prediction of its characteristics

ABSTRACT

Cryptomeria (*Cryptomeria japonica*) is the only local timber species that can be used for construction on La Réunion. However, its variable durability against basidiomycetes fungi and termites is an obstacle to its use locally, since the island's climatic conditions are particularly favourable to the degradation of bio-based materials.

This research consisted of accurately determining the natural durability of Cryptomeria wood against two ubiquitous basidiomycetes fungi (*Rhodonia placenta* and *Coniophora puteana*) and two termite species (*Coptotermes gestroi* from La Réunion and *Reticulitermes flavipes* from mainland France), using a very large sampling. For benchmarking purposes, Scots pine (slightly durable), Red Cedar (durable) and Cryptomeria cladding naturally weathered for 7 years in La Réunion, were tested under the same conditions, both leached or not, and exposed to xylophagous organisms in accordance with current European standard protocols. In addition, near infrared spectroscopy, coupled with chemometrics, was used to predict durability against basidiomycetes fungi.

The results confirm Cryptomeria susceptibility to termites and the very high variability of its durability against fungi. This species cannot be classified according to the classification principles for the EN 350 (2016) standard because the mass loss values (due to fungal decay) are distributed across the 5 durability classes, which range from "very durable" to "not durable".

Leaching and natural ageing give a better overall view of Cryptomeria performance, classifying it as "slightly durable to non-durable". Leaching has no influence on the performance of Red Cedar and Scots Pine, which remain classified as "durable" and "slightly durable", respectively.

Near infrared spectroscopy proved to be effective in predicting the natural durability of these species against fungi. Given the robustness of the model developed, this predictive tool can help in the optimization of the use of Cryptomeria by enabling non-destructive assessment of the durability of its timber to ensure optimum performance, in France's tropical overseas areas in particular.

Keywords: *Cryptomeria japonica*, Cryptomeria, natural durability, fungi, termites, near infrared spectroscopy, predictive model, wood performance.

Cryptomeria japonica de La Reunión: durabilidad natural ante los hongos basidiomicetos y las termitas, y contribución de la espectrometría del infrarrojo cercano a la predicción de sus características

RESUMEN

La criptomeria (*Cryptomeria japonica*) es la única especie maderera local utilizable para la construcción en La Reunión. Sin embargo, su durabilidad variable ante los hongos basidiomicetos y las termitas constituye un freno para el despliegue de su utilización en la isla, donde las condiciones climáticas son particularmente favorables a la degradación de los materiales de origen biológico.

Esta tesis tiene el objeto de determinar con precisión la durabilidad natural de esta madera frente a dos especies de hongos basidiomicetos ubicuos (*Rhodonia placenta* y *Coniophora puteana*) y dos especies de termitas (*Coptotermes gestroi* de La Reunión y *Reticulitermes flavipes* de Francia continental), realizando un amplio muestreo. A título comparativo, se utilizó pino silvestre (poco duradero), tuya gigante (duradera), así como revestimientos de criptomeria expuestos en La Reunión durante siete años, para realizar ensayos en las mismas condiciones, deslavados o no, y sometidos a los organismos xilófagos según los protocolos europeos normalizados en vigor. Como complemento, se utilizó la espectroscopía del infrarrojo cercano, emparejada con la quimiometría, para predecir la durabilidad frente a los hongos basidiomicetos.

Los resultados obtenidos confirman la sensibilidad de la criptomeria ante las termitas y demuestran una elevada variabilidad de su durabilidad ante los hongos. Las disposiciones previstas en la norma EN 350 (2016) no permiten catalogar esta especie porque los valores de pérdida de masa (debida a la degradación de los hongos) se distribuyen en las cinco clases de durabilidad que van de «muy duradera» a «no duradera».

El deslavado y el envejecimiento natural permiten comprender mejor el rendimiento de la criptomeria y catalogarla de «poco duradera a no duradera». El deslavado no tiene influencia en el rendimiento de la tuya gigante ni del pino silvestre, que continúan catalogados como «duradera» y «poco duradero» respectivamente.

La espectroscopía del infrarrojo cercano es, en definitiva, una herramienta eficaz para la predicción de la durabilidad natural de estas especies frente a los hongos. Con la ayuda de nuestro sólido modelo, esta herramienta predictiva contribuirá a un uso optimizado de la *Cryptomeria japonica*, permitiendo una evaluación no destructiva de la durabilidad de esta madera con el objetivo de garantizar un rendimiento óptimo, en particular en zonas ultramarinas tropicales.

Palabras clave: *Cryptomeria japonica*, criptomeria, durabilidad natural, hongos, termitas, espectroscopía del infrarrojo cercano, modelo predictivo, rendimiento de la madera.

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Photo 1. Plantations de *Cryptomeria japonica* dans la forêt de Bébour sur l'île de La Réunion. Le cryptoméria est la seule ressource de bois local exploitable et utilisable dans la construction.
Photo J. Vuillemin.

Photo 1. *Cryptomeria japonica* plantations in the Bébour forest on La Réunion. Cryptomeria is the only local timber resource that can be extracted for use in construction.
Photo J. Vuillemin.

Foto 1. Plantaciones de *Cryptomeria japonica* en el bosque de Bébour de la isla de La Reunión. La criptomeria es el único recurso maderero local explotable y utilizable en la construcción.
Foto J. Vuillemin.

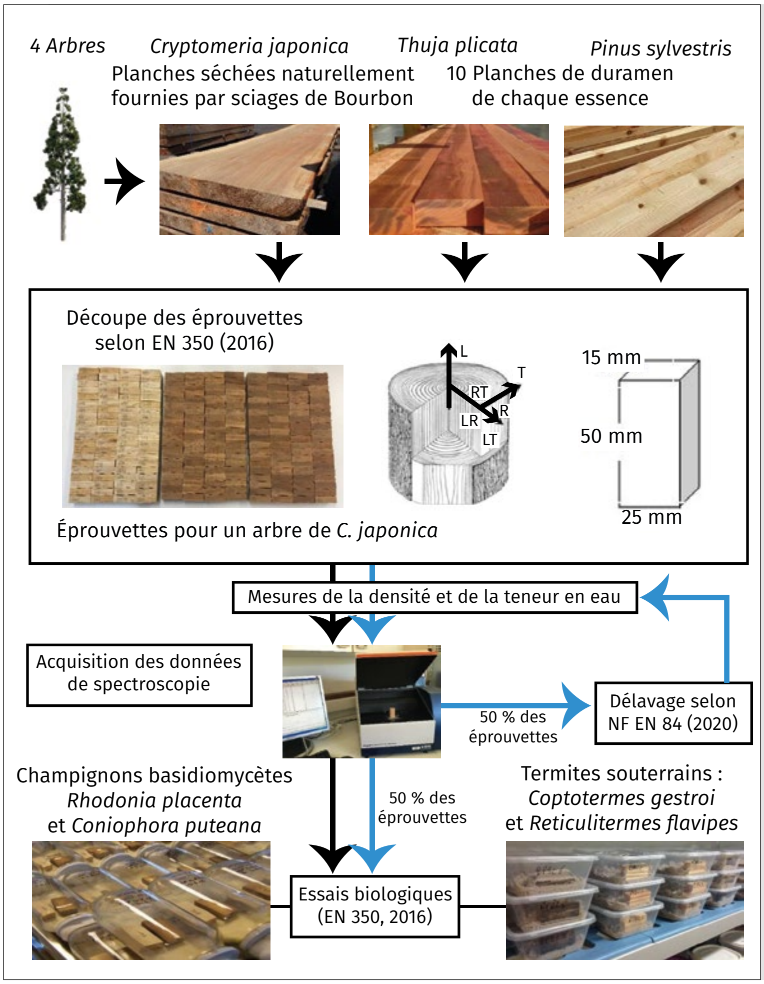

Figure 1. Représentation schématique de l'échantillonnage en cryptoméria, pin sylvestre et Red cedar et des expérimentations réalisées. Après conditionnement, chaque éprouvette de bois est mesurée et pesée, avant d'être soumise à la spectroscopie proche infra-rouge (SPIR) non destructrice. La moitié des échantillons sont délavés selon la norme EN 84 (épreuves de vieillissement accéléré des bois traités avant essais biologiques – épreuve de délavage, 2020). Les éprouvettes sont ensuite soumises à la dégradation de champignons lignivores et de termites selon les directives de la norme EN 350 (méthodes d'essai et de classification de la durabilité vis-à-vis des agents biologiques du bois et des matériaux dérivés du bois, 2016). Les résultats d'essai biologiques permettent de qualifier la classe de durabilité des bois et d'évaluer la variabilité liée à chaque essence. Les résultats de durabilité vis à vis des champignons sont mis en regard des résultats de SPIR afin d'établir un modèle prédictif.

Figure 1. Schematic representation of Cryptomeria, Scots Pine and Red Cedar sampling and experiments. After conditioning, each wood sample was measured and weighed before its exposure to non-destructive near infrared spectroscopy (NIRS). Half the samples were leached according to EN 84 (accelerated ageing of treated wood prior to biological testing – leaching procedure, 2020). The specimens were then exposed to wood-destroying fungi and termites in accordance with EN 350 guidelines (testing and classification of the durability of wood and wood-based materials against biological agents, 2016). The durability class of the wood was given by the biological test results, which also served to assess the variability associated with each species. The results for durability against fungi were compared with SPIR results to establish a predictive model.

Figura 1. Representación esquemática del muestreo de criptomeria, pino silvestre y tuya gigante, y experimentos realizados. Después del acondicionamiento, cada probeta de madera se mide y pesa, antes de someterse a la espectroscopía del infrarrojo cercano (SPIR) no destructiva. La mitad de las muestras se deslavan según la norma EN 84 (pruebas de envejecimiento acelerado de las maderas tratadas previas a los ensayos biológicos – prueba de deslavado, 2020). Las probetas se someten a continuación a la degradación por hongos xilófagos y termitas según las directivas de la norma EN 350 (métodos de ensayo y de clasificación de la durabilidad frente a agentes biológicos de la madera y de los materiales derivados de la madera, 2016). Los resultados de los ensayos biológicos permiten determinar la clase de durabilidad de las maderas y evaluar la variabilidad de cada especie. Los resultados de durabilidad ante los hongos se compararon con los resultados de SPIR para establecer un modelo predictivo.

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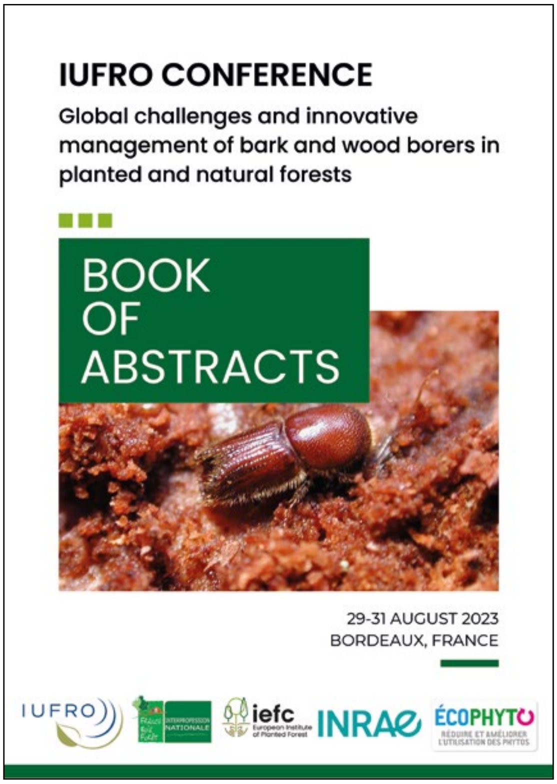

IUFRO CONFERENCE PROCEEDINGS - BOOK OF ABSTRACTS GLOBAL CHALLENGES AND INNOVATIVE MANAGEMENT OF BARK AND WOOD BORERS IN PLANTED FORESTS

29TH AUGUST – 1ST SEPTEMBER 2023, BORDEAUX, FRANCE

EUROPEAN INSTITUTE OF PLANTED FOREST

Global changes, including climate change and economic globalisation, pose serious threats to the health of the world's forests by favouring the emergence or invasion of an increasing number of forest pests. Wood and bark beetles play a prominent role in this context due to the spatial extent and intensity of their damage. There are numerous examples of massive attacks by these insects on all continents, with long or chronic outbreaks, causing the mortality of a considerable number of trees or forest areas. Their diversity, capacity for natural or human-assisted dispersal, frequent association with pathogenic fungi, and their direct effects on the survival of trees make some scolytid species the most serious pests of natural or planted forests. Responding rapidly to rising temperatures or droughts, benefiting from storm or fire damage, they have become one if not the primary cause of disturbance to forest ecosystems, drastically accelerating the expected longer-term effects of climate change.

Because of the scale and the recent increase in wood and bark beetle damage, it seems useful and necessary to take stock of the state of scientific knowledge concerning the epidemiology of species and above all, the means of monitoring and managing their populations. Many approaches and methodologies can be applied to the study and control of these insects, which justifies the gathering of knowledge and skills of many IUFRO working groups and task forces. This joint conference aimed to provide knowledge and tools for action for forest scientists and practitioners searching for solutions to mitigate the risk of bark beetle attacks.

The conference was held in Bordeaux, France, where recent heat waves have caused massive outbreaks of the typographer bark beetle, where fires on an unprecedented scale have created the conditions for the emergence of large populations of the stenographer bark beetle, and where reforestation plantations are regularly subjected to repeated attacks by the pine weevil. But these examples are not limited to France and colleagues around the world were invited to share their findings to better manage the risk of renewed attacks by native or exotic bark beetle species.

- Sessions.
- Monitoring and management of *Hylobius abietis*.
- Population dynamics of *Ips typographus*.
- Molecular and physiological studies of wood-boring insects.
- Drought and heat-related host tree–bark beetle interactions.
- Invasions of bark beetles and wood borers.
- Precision pest management of bark and wood borers.
- Novel monitoring and modelling tools for the management of bark beetles.

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INTERNATIONAL CONFERENCE ON THE THEORY AND PRACTICE TO ADDRESS DEFOLIATING INSECTS, INVASIVE PESTS AND BIOLOGICAL CONTROL OF INSECTS AND PATHOGENS IN FORESTS

21ST – 23RD AUGUST 2024, TOKYO, JAPAN

IUFRO
Interconnecting Forests, Science and People

The health of forests worldwide is threatened by insect pests and diseases. For example, outbreaks of defoliating insects reduce production efficiency, and the continued introduction of invasive pests is stretching the available capacity and resources to manage these threats. Research in various disciplines is needed to unlock new approaches to manage forest pests, including a shift in focus from chemical to biological control. In addition, many of the current threats require cross-boundary and multi-disciplinary approaches. This joint meeting will exchange information on the theory and practice to address defoliating insects and invasive species of forests, including biological control and other approaches. The meeting will include researchers from different disciplines and countries and provide an overview of the challenges to forest health, and research-driven responses to these challenges.

Contact:
René Eschen, e-mail: R.Eschen@cabi.org

To get more information:
https://tropicalwood.sciencesconf.org/

GRIMA N. (IUFRO), MOEINI-MEYBODI H. (UNFF SECRETARIAT), SCOTT T. (UNDP), XIA Z. (FAO) (LEAD AUTHORS), 2023.

ISSUE BRIEF – FORESTS, ENERGY AND LIVELIHOODS

IUFRO, 19 P.

A new Issue Brief was launched during the 18th session of the UN Forum on Forests. The Issue Brief *Forests, Energy and Livelihoods* aims to inform discussions at the hybrid global event at UNHQ in New York, convened on 4 April by the Bureau of the 18th session of the UNFF and ahead of the UN General Assembly Summit on Sustainable Development Goals in September.

More integrated approaches between forests, energy, and livelihoods can accelerate progress towards the Sustainable Development Goals, according to a joint brief published on 4th April 2023 by the UN Forum on Forests Secretariat (UNFFS), the Food and Agriculture Organization of the United Nations (FAO), the International Union of Forest Research Organizations (IUFRO) and the United Nations Development Programme (UNDP).

“Particularly given the current global economic situation, the prospect of a global recession and increased energy and commodity prices, it is vital to recognize the role of forests and sustainable management of forests in achieving sustainable development,” the four organizations say in the brief.

“Forests provide solutions for addressing many developmental challenges. More than 1.6 billion people worldwide strongly depend on forests for food, medicine, fuel, and for their livelihoods.”

IUFRO’s Dr. Nelson Grima is one of the lead authors of the Issue Brief. He says: “It is also imperative to invest in the advancement of forest-related research in all its different fields, both at the theoretical and implementation level, considering the needs and knowledge of stakeholder groups.”

GLOBAL FOREST GOALS

Food and Agriculture Organization of the United Nations

IUFRO Interconnecting Forests, Science and People

United Nations FORUM ON FORESTS

UNDP

To download the Issue Brief:
https://www.iufro.org/fileadmin/material/events/unff18/ISSUE-BRIEF-Forests-Energy-Livelihoods-March2023.pdf

To access to the video recording of United Nation Forum of Forests session:
https://media.un.org/en/asset/k1h/k1honsc5cj

IRG55 Annual Meeting

The IRG55 meeting of the International Research Group on Wood Protection will be held from 19th to 23rd May 2024, in the Crown Plaza Hotel in Knoxville, in the state of Tennessee USA.

It will be a great venue and a fabulous meeting, so please start planning now to join the conference.

The International Research Group on Wood Protection (IRGWP) is the leading global organization for the dissemination of scientific information on wood protection products.

More information:

https://www.irg-wp.com/IRG55/index.html

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ISBN: 978-2-87614-838-3 (relié)

Schedule for IRG55

Deadlines for RCA applications to attend IRG55:
December 15th, 2023
Submission of RCA applications for IRG55.

Deadlines for Papers and Posters Submissions:
March 1st, 2024
Submission of Papers to IRG Secretariat.

April 1st, 2024
Submission of Poster Abstracts to IRG Secretariat.

Deadline for Registration without late fees:
April 20th, 2024
IRG55 Registration without late payment penalty.

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