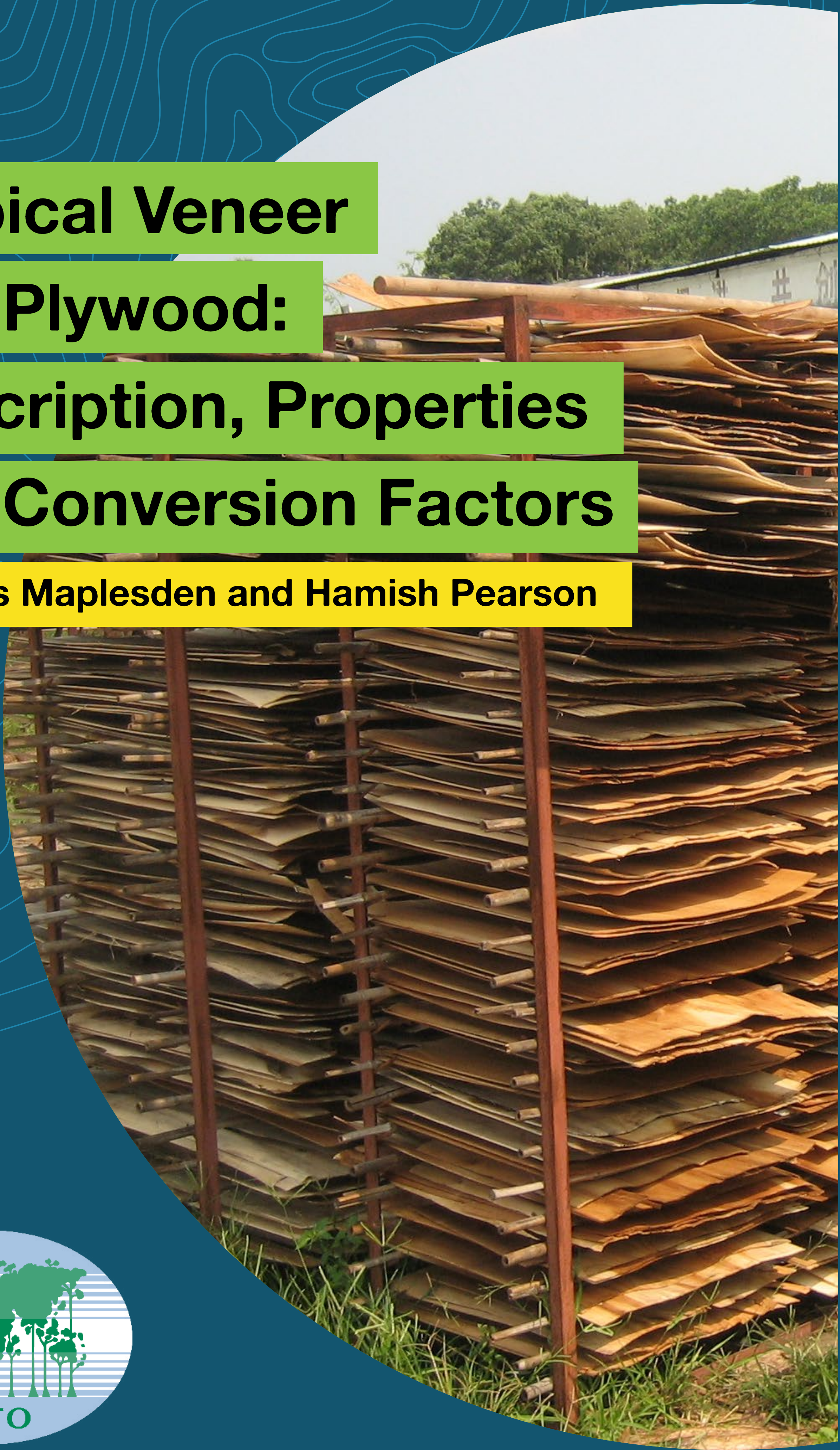
Tropical Veneer and Plywood: Description, Properties and Conversion Factors

Frances Maplesden and Hamish Pearson



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ITTO is an intergovernmental organization promoting the conservation, restoration and sustainable management, use and trade of tropical forest resources. Its members represent 80% of the world's tropical forests and 90% of the global trade in tropical timber and timber products. ITTO develops internationally agreed policy documents and guidelines to promote sustainable forest management and forest-based enterprises and assists tropical member countries to adapt such policies and guidelines to local conditions and to implement them in the field through projects. In addition, ITTO collects, analyzes and disseminates data on the production and trade of tropical timber and is the foremost source of information, statistics and trends related to the global tropical timber economy. Since it became operational in 1987, ITTO has funded more than 1200 projects, pre-projects and activities valued at more than USD 430 million.

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Front cover: veneer sheets, Province of Hainan, China. Photo: JC Claudon/ITTO

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Introduction

Veneer sheets and veneer kiln, Province of Hainan, China. Photo: JC Claudon/ITTO

1.1 Background

Accurate trade volume estimates are important to enable transparency in the tropical wood products trade as this data can be used to estimate national and international wood requirements and balances and can indicate illegally logged roundwood in the supply chain. The International Tropical Timber Organization (ITTO), the Food and Agriculture Organization of the United Nations (FAO), the United Nations Economic Commission for Europe (UNECE) and Eurostat use conversion factors regularly to report and analyse trade and production data on forest products. Conversion factors allow estimating of traded volumes or weight when only one of these variables is reported.

ITTO regularly reports trade and production data in comparable units for all its member countries (37 producer countries and 39 consumer countries). This data is derived from several sources including the Joint Forest Sector Questionnaire (JFSQ) and supplementary sources such as COMTRADE (the UN commodity trade database). Although country data is reported to the ITTO Secretariat via the JFSQ in standard ITTO-specified units, this data is often incomplete and other information sources are required. These sources may report data in non-standard units (such as weight and surface area), requiring conversion to standardised international reporting units. Trade data available in COMTRADE is frequently reported only by weight, whereas ITTO reports trade data for tropical primary wood products by volume. Conversions from volume to weight are also used for determination of biomass and carbon, which are quantified in weight units e.g., for calorific value content determination and for comparison with other sources of biomass.

Many tropical species are not listed in the World Customs Organization's Harmonized System (HS) Nomenclature of trade classification. Exports of tropical veneer by tropical countries are often reported by weight or area, and exports of tropical plywood are often reported by weight. Single, average weight to volume adjustments for plywood and tropical veneer have been used since ITTO initiated reporting of tropical wood products trade in 1987. These adjustments are not specific to species or country of origin, although there is known to be substantial variation in conversion values between species and their environmental conditions (Rijsdijk and Laming 1994; CIRAD 2015; Dinwoodie 2000; USDA 2010). The mix of species utilised in tropical plywood manufacture, and the major exporting and importing countries, have also changed over that period (ITTO 2022).

The overall purpose of this analysis is to improve the accuracy of reported trade volumes of tropical primary wood products and therefore improve transparency in the tropical wood products trade. In an earlier study, ITTO derived conversion factors from weight to volume for tropical logs and sawnwood for major tropical exporting countries based on the weighted average of the species exported and known data on wood and bark density and moisture relationships (Maplesden and Pearson 2021). An FAO study has also reviewed forest products conversion factors in a more general context (FAO *et al*. 2020). The aim of this study is to build on and complement these studies by deriving theoretical conversion factors from weight to volume for tropical veneer and tropical plywood, and from square metres to volume for tropical veneer by species, for major tropical exporting countries.

1.2 Structure of this report

Sections 2-5 provide background on the production, composition and technical properties of tropical veneer and plywood. Section 2 provides information on product descriptions and definitions of veneer and plywood, plywood production processes, and plywood grading. In Section 3, information on major end uses and key markets for tropical veneer and plywood is reviewed. Section 4 determines the major species used in tropical veneer and plywood manufacture and trade, as well as the main sizes and composition of tropical veneer and plywood.
Section 5 provides information on the technical properties of plywood. Sections 6-7 present theoretical calculations of tropical plywood and veneer conversion factors, including the methodology, assumptions used and a discussion of the results.

2

Description of veneer and plywood

2.1 Description of veneer

Veneers are thin sheets of wood which are rotary cut (peeled), sliced or sawn from a log, bolt or flitch. Peeling and slicing are the most common production techniques, and these processes are described in detail in Wagenführ *et al.* (2023).

Veneers are used in the following applications:

- Decorative uses as a coating material for substrates such as wood-based panels
- Structural/industrial applications where veneer plies are glued together to produce material such as plywood, laminated veneer lumber (LVL) or moulded plywood

Veneer thickness depends on its end use. Rotary peeling is used to produce thicker veneers, usually in the range of 1.2 to 3.4mm, for plywood and structural applications. Sliced veneer is generally used to produce thinner veneers for decorative uses in the range of 0.5mm (standard thickness) to 2.5mm (surface flooring layers) thickness.

Most decorative veneer is sliced from flitches after the log is cut into quarters. Decorative veneers are used in decorative appearance applications, mostly in furniture production, door and panelling applications, various veneer-based accessories, and indoor design of the automotive, yacht and airplane industries. The decorative effect of veneer is strongly based on the texture of the wood and the direction of the cut, rift cut or tangential cut, and the inherent natural colour of the wood, which can be enhanced by the final surface coating (Wagenführ *et al.* 2023).

Rotary cut veneers are mainly used as the base material in the manufacture of plywood and LVL for structural uses. The peeling process is described in detail in Wagenführ *et al.* (2023).

2.2 Description of plywood

ITTO's definition of plywood is "a panel consisting of an assembly of veneer sheets bonded together with the direction of the grain in alternate plies generally at right angles. The veneer sheets are usually placed symmetrically on both sides of a central ply or core that may itself be made from a veneer sheet or another material. It excludes laminated construction materials (e.g. glulam), where the grain of the veneer sheets generally runs in the same direction, bamboo plywood and cellular board." Tropical plywood must have at least one outer sheet of tropical veneer and can therefore include non-tropical veneers in the panel composition.

Plywood is a wood-based panel comprised of an assembly of two or more plywood layers (called wood veneers or plies) in combination with a core. The wood veneers are laminated together with the layers normally oriented at right angles to the previous layer (Wagenführ *et al.* 2023). Normally, the structure is symmetric, resulting in an odd number of layers which can vary from 3 to 21 layers. The alternation of the grain reduces the tendency of the board to split when nailed at the edges, reduces expansion and shrinkage, improves dimensional stability, and improves strength characteristics of the board. The centre layers may be veneer, sawnwood, particleboard, or fibreboard although all-veneer construction is most common in construction and industrial plywood. Tropical plywood is designated commercially by the face veneer timber species (e.g. okoumé-faced plywood).

Blockboard or laminboard and battenboard, which is also included in ITTO's definition of tropical plywood when faced with a tropical veneer, is termed "core plywood" as it comprises at least three veneers (face, core & back). However, it differs from veneer plywood as the core is comprised of strips of solid timber or veneer laid on edge which is bonded or otherwise joined together to form a slab, and then faced with veneers on each side, with the direction of the grain of the core strips at right angles to that of the adjacent veneers (WPIF 2014).

Laminated veneer lumber (LVL) is also classified as tropical plywood when faced with a tropical veneer. LVL is predominantly composed of lengthwise veneer layers although up to 15% of the veneers may be perpendicular to the grain. LVL is typically used as structural members for lintels, beams, mid-floors and roofs in residential and commercial building projects.

Chinese worker assembling plywood sheets, Province of Hainan, China. Photo:JC Claudon/ITTO

2.3 Plywood production process

In plywood production, prior to peeling or slicing, the logs are generally heated via warm water immersion or steamed to increase the wood plasticity and moisture content for high-quality cutting and achieving a smooth veneer surface, in addition to enhancing the colour of the wood. The veneers are then dried to a moisture content of about 4% to 12%, to enable gluing of veneers. The main types of resin used are urea-formaldehyde (UF) for interior uses, phenol-formaldehyde (PF) for panels suitable for use in humid and exterior environments, and melamine-urea-formaldehyde (MUF) used in protected exterior applications. The veneer sheets are glued and subjected to pressure and heat resulting in a pressed and cured panel.

2.4 Plywood grading

Two classes of plywood are commonly available, covered by separate standards: (a) construction and industrial plywood, in which performance is more important than appearance and (b) hardwood and decorative plywood. Decorative hardwood plywood is categorised by species and characteristics of the face veneer, bond durability, and composition of centre layers (USDA 2010).

Plywood face veneer is the visible, exposed veneer of a plywood product. It is of a superior grade to the back veneer, which is the other side of the product (i.e.as opposed to the inner veneers). When the two exposed veneers are of equal grade, either one can be considered the face or back veneer. The core consists of the layer or layers of one or more material(s) that are situated between the face and back veneers. The core may be composed of a range of materials, including but not limited to veneers, particleboard and medium density fibreboard (MDF).

Tropical plywood products are generally graded according to end-use (hardwood and decorative/construction and industrial) with a focus on qualities related to bonding, exposure capability to moisture and weathering, strength and stiffness (structural uses), and surface and back quality imperfections (decorative uses). Formaldehyde emissions, inflammable properties, and dimensional qualities can also be important.

Normal grading systems for plywood use the letters A, B, C and D, where A is the best quality, with virtually no blemishes and very well sanded. Grade D typically contains up to the maximum allowed number of blemishes. The letter grades typically come in pairs, where one letter refers to the “better” side (i.e. the face) and the other letter referring to the back (Maplesden and Johnson 2016).

Samples of lauan plywood, Wood and Plywood Museum, Shinkiba Koto City Tokyo. Photo: JC Claudon/ITTO

3

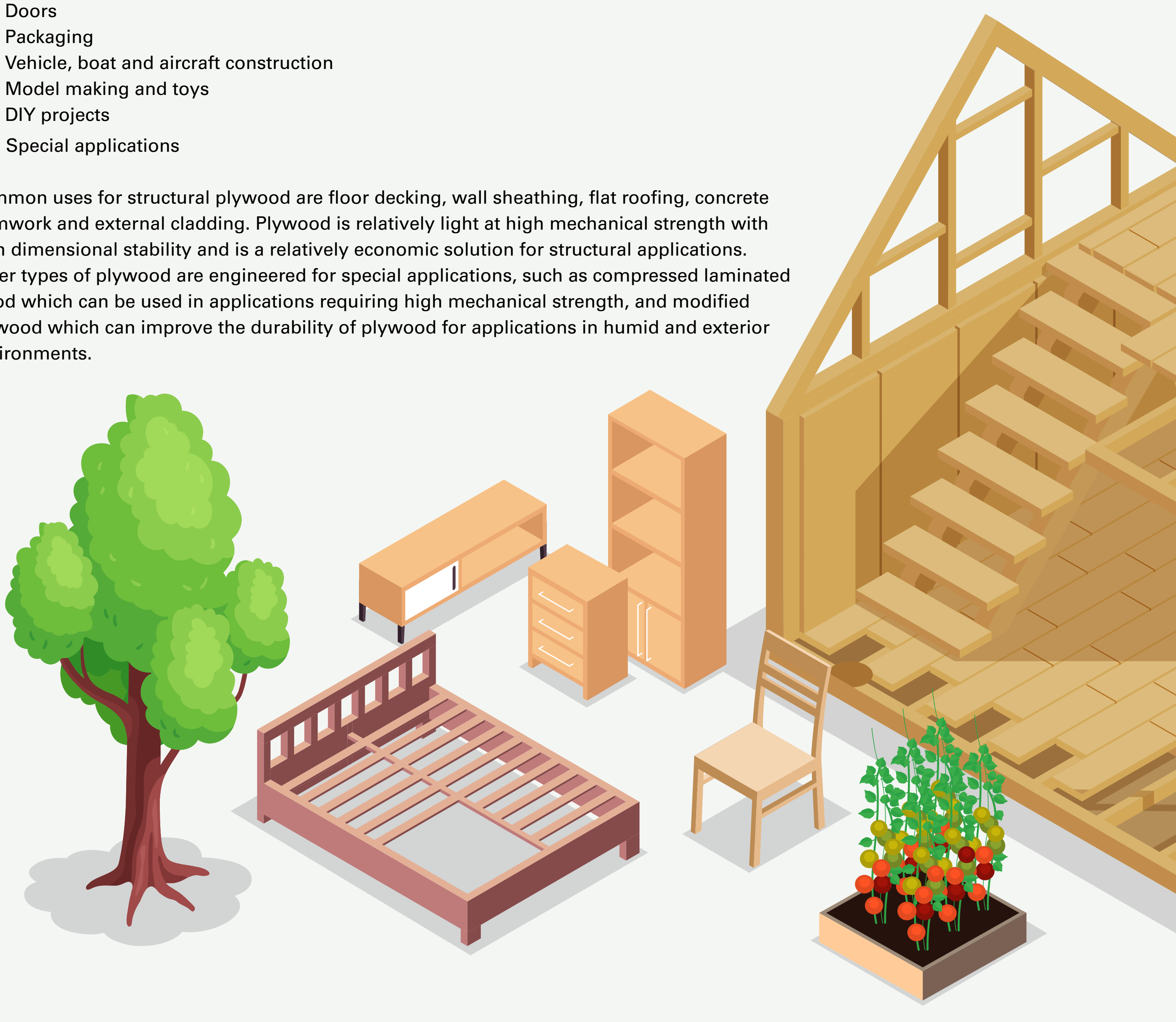
Uses and markets for tropical veneer and plywood

The range of species and adhesives available has enabled plywood to be engineered to have specific properties, making it suitable for a wide range of applications ranging from structural, marine, utility (non-structural) and specialty applications (from flexible plywood to compressed plywood). The main applications of plywood (for all species) at a global level by volume in 2017 (the latest data available) were building and construction (39%), furniture (30%), transport applications (13%), packaging (8%) and other applications (10%) with about 80% of the total plywood production used in outdoor uses (Wagenführ *et al*. 2023).

Key markets for plywood in interior and exterior applications are the following:

- Construction, for parts of load-bearing construction, walls, ceilings, roofing and floors
- Concrete shuttering (formwork)
- Furniture and interior construction, for cupboards, shelves, tables, chairs and the substructure of upholstered furniture
- Stages and floors
- Doors
- Packaging
- Vehicle, boat and aircraft construction
- Model making and toys
- DIY projects
- Special applications

Common uses for structural plywood are floor decking, wall sheathing, flat roofing, concrete formwork and external cladding. Plywood is relatively light at high mechanical strength with high dimensional stability and is a relatively economic solution for structural applications. Other types of plywood are engineered for special applications, such as compressed laminated wood which can be used in applications requiring high mechanical strength, and modified plywood which can improve the durability of plywood for applications in humid and exterior environments.



A wide range of species of tropical veneers (see section 4) are used as the face veneer in the manufacture of hardwood decorative plywood, which is used mainly in furniture and interior applications including decorative wall panels and furniture and cabinet panels where appearance is more important than strength. Most of the production is intended for interior or protected uses, although a very small proportion is made with adhesives suitable for exterior service, such as in marine applications (USDA, 2010).

Veneer quality is a factor in construction and industrial plywood based on visually observable characteristics. Knots, decay, splits, insect holes, surface roughness, number of surface repairs, and other defects are considered. Veneer species and visual characteristics are a major factor in categorisation of hardwood and decorative plywood.

In construction applications, tropical plywood is generally regarded as having superior technical qualities to softwood plywood in terms of density, strength and board quality. Indonesia's exports of plywood to Japan, traditionally a major market for Indonesian plywood, have been used predominantly in floor base construction, whereas Malaysia's exports have been used in concrete formwork applications (ITTO 2022).

In marine applications, marine plywood has been developed for ship/boat building and is manufactured from durable face and core veneers with few defects and has a very high performance in humid and wet conditions. Marine plywood is also commonly used in construction applications where the risk of failure warrants the additional cost (WPIF 2014). Okoumé *(Aucoumea klaineana)* is a relatively low-density tropical species, with only a slightly durable standards rating in most codes and standards. However, it is an accepted standard for marine plywood (British Standard BS 1088), using high quality veneers with negligible core gaps which limits the trapping of water in the plywood, providing a solid and stable glue bond (Plywood for Europe 2013). Its major advantages are its light weight and high strength to weight ratio.

In the important China market, it is estimated that more than 95% of veneer produced in China is made by peeling and less than 5% by slicing, although this estimate includes all species of softwoods and hardwoods. China's consumption of plywood by end use has been estimated as: construction 26%, interior decoration 21%, furniture 12%, exports 13%, packaging 8%, flooring and joinery 7%, other uses 13% (CAF 2017). A survey of 308 veneer and plywood manufacturers in China identified that tropical plywood exports are assumed to be mostly poplar or eucalypt plywood with a tropical veneer overlay, used predominantly in furniture, interior panelling and flooring end uses (CAF 2017).

4

Major tropical plywood and veneer species and sizes

4.1 Tropical species used in veneer and plywood manufacture

More than seventy species (tropical and non-tropical) are used worldwide for plywood production (Wagenführ *et al.* 2023). A review of the available literature and trade websites (see section 7), indicates several species (tropical and non-tropical) used in tropical plywood manufacture (Table 1).

Table 1: Wood species used in tropical veneer and plywood production

Pilot (Trade) name	Some common names	Botanical names	Countries/regions using species in tropical veneer/ plywood production
acacia	arr; black wattle; kayu safoda; kra thin tepa; mangge hutan; tongke hutan	*Acacia mangium* Willd.	Viet Nam, Southeast Asia, PNG
acajou d'Afrique	khaya; African mahogany	*Khaya ivorensis* A. Chev.	Ghana, West Africa
ako	ako; kyen kyen; antiaris, chenchen	*Antiaris Africana* Engl.; *Antiaris toxicaria* Lesch.	Ghana
alan	alan-batu; red selangan	*Shorea albida* Symington	Malaysia, China
andoung	andoung; ekop	*Monopetalanthas* spp.	West Africa
aniégré	asanfena	*Aningeria* spp.	Cameroon, Ghana
ayous	obeche; wawa; African whitewood	*Triplochiton scleroxylon* K. Schum.	Cameroon, West Africa
balau, red	red selangan batu, balau merah	*Shorea* spp.	Malaysia
balau, yellow	bangkirai, selanagan batu	*Shorea* spp.	Indonesia
baromalli	baromalli	*Catostemma commune Sandw.*	Guyana
batai	falcata; sengon; albizia	*Paraserianthus falcataria* I. C. Nielsen; *Albizia falcata*	Indonesia, Malaysia
bintangor	calophullum; penaga	*Calophyllum* spp.	PNG, China, Malaysia
cedro	cedralla, red cedar	*Cedrela odorata* L.	Brazil, Suriname
essia	abalé	*Petersianthus macrocarpus* Liben	Ghana
eyong	bongele; eyong	*Eribroma oblongum* Pierre	Cameroon
gerutu	gerutu; white meranti; gerutu pasir, meranti gerutu; meruyun; heavy white seraya	*Parashorea* spp.	Malaysia
hevea	rubber tree, rubberwood	*Hevea brasiliensis* Muell. Arg.	Malaysia, Indonesia, China, Viet Nam, Thailand
ilomba	eteng	*Pycnanthus angolensis* Warb.	Cameroon
ipê	ipê; ironwood	*Tabebuia* spp.; *Handroanthus* spp.	Brazil
iroko	iroko; kambala; odoum	*Milicia excelsa* C. C. Berg; *Clorophora excelsa* Benth. & Hook.	West Africa
jelutong		*Dyera* spp.	Malaysia
kadam	jabon; kadam; kalempayan	*Neolamarckia cadamba* Bosser; *Anthocephalus chinensis* Cadamba Miq.	Indonesia
kamarere; saligna gum	eucalypt	*Eucalyptus deglupta; Eucalyptus grandis; Eucalyptus saligna*	China, Indonesia
kapur	kapur; keladan; petanang	*Dryobalanops* spp.	Malaysia
kedondong	kedondong; thadi, upi	*Canarium* spp.	Malaysia
kelat	kelat; obar	*Syzgium* spp.	Malaysia
keruing	apitong; gurjun; kanyin	*Dipterocarpus* spp.	Myanmar, China, India
klinki	klinki; hoop pine	*Araucaria cunninghamii* Sweet	PNG, USA
koto	kyere	*Pterygota macrocarpa* K. Schum.	Ghana
limba	ofram; fraké	*Terminalia superba* Engl. & Diels	Cameroon, Rep. of Congo
mahang	mukuhakula	*Macaranga* spp.	Malaysia
mahogany	mahogany; mogno; caoba	*Swietenia macrophylla* King	Brazil

Pilot (Trade) name	Some common names	Botanical names	Countries/regions using species in tropical veneer/ plywood production
makoré	makoré; baku; abacu	*Tieghmella heckelli* Pierre	Ghana
medang	medang	*Neolitsea latifolia* (Bloom) S. Moore	Malaysia
meranti, light red meranti, dark red meranti, white meranti, yellow	lauan; seraya	*Shorea* spp.	Malaysia, Indonesia, Philippines, PNG, China
merbau	kwila	*Intsia bijuga* Kuntze	PNG, Indonesia, Malaysia
mersawa	mersawa, Bella Rosa	*Anisoptera thurifera* Blume	Southeast Asia, PNG, USA, China
mixed light hardwoods	Includes several species, including (but not restricted to) meranti, batai, rubberwood, nyatoh, sepetir, jelutong, and kadam		Malaysia, Indonesia, China
mixed medium hardwoods	Includes several species, including (but not restricted to) kelat, kapur and keruing		Malaysia
nyatoh	nyatoh; pencil cedar; mayang	*Palaquium burckii* H. J. Lam	PNG
okoumé	okoumé	*Aucoumea klaineana* Pierre	Gabon, Ghana, Rep. of Congo, China
onzambili	onzambili; angonga	*Antrocaryon micraster* A. Chev.	Cameroon
ozigo	Safunkala, assas	*Dacryodes buettneri* H. J. Lam	Cameroon, Equ. Guinea, Gabon, DRC
padauk amboina	PNG rosewood; Indian padauk; Andaman padauk: narra; amboina	*Pterocarpus indicus* Willd.	PNG
pelong	pelong; pelaju	*Pentaspadon velutinus* Hook f.	Malaysia
pine, radiata	radiata pine	*Pinus radiata* D. Don	China, Malaysia
poplar	Chinese white poplar; mao bai yang	*Populus tomentosa* Carrière	China
rengas	gluta; rengas; kerbau; jalang	*Gluta* spp.; *Melanochyla* spp.	PNG, Malaysia
sapelli	sapele	*Entandrophragma cylindricum* Sprague	Cameroon, Ghana, China
sepitir	krakas, krathon, sindur	*Sindora* spp.	Malaysia
sesendok	bakota, basswood, terbulan	*Endospermum* spp.	Malaysia
sipo	utilé	*Entandrophragma utile* Sprague	West Africa
sumauma	fromager; fuma, sumauma; ceiba-fromager	*Ceiba pentandra* Gaertn.	Ghana, Cameroon
teak	giati, jati, kyun, may sak	*Tectona grandis* L. f.	India, Myanmar, China,
virola	baboen	*Virola* spp.	Guatemala, Suriname
wengé	awong, awoung, jambire	*Milettia laurentii* De Wild.	Central Africa
yemane	gamar; yemane; gmelina	*Gmelina arborea* Roxb.	Indonesia, Philippines, Southeast Asia

Sources: ATIBT 2016; ATIBT 2024; Bolza and Keating 1972; ITTO 2024; ITTO 2022; Rijsdijk and Laming 1984; Suffian et al. 2023; USDA 1984; WWF 2013.

Note: Pilot names are those listed in ATIBT (2016).

Tropical plywood is manufactured either from the same species throughout the panel, or from a combination of species, in which there is a differentiation between species used as core veneer (tropical or non-tropical) and that used as the face veneer or as a decorative overlay (tropical only). The declining availability and rising prices of peeler logs of tropical species from natural forests has led to the extensive use of fast-grown plantation species such as pine, poplar, eucalypts, hevea (rubberwood) and acacia as core raw materials in tropical plywood manufacture. In addition, lower density tropical species commonly used in Malaysia and Indonesia such as those classified as "mixed light hardwoods" are also being used extensively (Suffian *et al*. 2023). Acacia, eucalypt and hevea wood veneers have high mechanical strength, weather resistance, and good dimensional stability which is important in construction end uses.

There are many species exported as tropical veneer and used as face veneers in tropical plywood manufacture. The species identified in Table 1 have been exported and/or utilised in tropical plywood manufacture in the countries listed, as identified from the available literature and trade websites. There may, however, be other species and countries which have not been identified but it is assumed that the list covers the major species traded. Several evaluations of the suitability of lesser-known tropical species (and plantation species) for plywood production have been undertaken such as by Gaiotto (1998), Kallakas *et al*. (2020), Muhammad-Fitri *et al*. (2017) and Rahman *et al*. (2021), suggesting that the range of species used in tropical plywood production is expanding. However, data on the volume of tropical veneer and plywood exported from ITTO member countries by species is very limited and is complicated by the use of combinations of species used in tropical plywood manufacture, although there is some anecdotal information on the types of species used in tropical veneer and plywood production and trade.

Malaysia is one of the few countries where data is available on species used in veneer and plywood production, although the data is only available for the state of Peninsular Malaysia, which accounts for only 10% of Malaysia's veneer and plywood production compared with the state of Sarawak (70%) and Sabah (20%) (Timber Trade Portal 2024). A recent study on the density of plywood produced in Malaysia states that most of the timber used in Peninsular Malaysia is of mixed light hardwoods (90%), followed by medium hardwoods (8%) and a small proportion of other wood types (Suffian *et al*. 2023). Hevea (rubberwood) is the major species used (44% of Peninsular Malaysia's production of 440,000 m^3), followed by kedondong (7%) and several other species which include medang, red meranti, mahang, rengas, mersawa, pelong, gerutu and sesendok. Kelat (2% of production) and keruing (2%) are commonly used medium density hardwoods. There are a number of unidentified species which are mostly light hardwoods (Suffian *et al*. 2023). Several Malaysian commercial plywood trade websites list meranti, kapur, keruing and mixed light hardwoods as common species used in listed plywood products. Most of Malaysia's tropical plywood exports are of structural grade plywood.

China, the world's largest producer and exporter of plywood, uses wood species from both domestic and imported sources in its plywood manufacturing industry. It is estimated that about 70% (50% poplar species, 20% eucalypt species) of the wood volume used in China's plywood production is of plantation species, with 30% from other non-plantation species (CAF 2017). Tropical plywood is mainly manufactured with core veneers of poplar and eucalypts, and face veneers of imported tropical veneers. China also produces veneers manufactured from imported tropical logs. The source of imported tropical raw material has shifted in recent years from predominantly Malaysia and Indonesia to African supplying countries (CAF 2017), although an extensive range of species is listed in Chinese export companies' trade websites (including okoumé, teak, bintangor, pencil cedar (nyatoh) and sapelli). Most of China's tropical plywood exports are for furniture, interior decoration and wood flooring.

Indonesia had traditionally used natural forest species such as meranti, keruing, nyatoh, teak and mahogany in plywood manufacture. Merbau and meranti are commonly used in the production of tropical plywood for construction and decorative plywood panels. Plantation species such as sengon (albizia) are now used extensively in the industry, along with eucalypts and hevea, as the availability of natural species has declined, and prices have escalated.

Information on Viet Nam's veneer and plywood industry is more limited, although anecdotal information from trade websites suggests that acacia, eucalypts, hevea, styrax (*Styrax* spp.) and mixed light hardwoods are used extensively as core veneers, with several tropical species as face veneers, including okoumé, bintangor, and keruing (for flooring plywood).

In Gabon, the major species used in veneer and plywood manufacture is okoumé, followed by sapele. In Ghana, the other major exporter of veneer and plywood from the West African region, rotary veneer exports are reported for ceiba (sumauma), chenchen (ako), essia and ofram (limba), and exports of sliced veneers of asanfena (aniégré), avodire, chenchen, mahogany, makoré, odoum (iroko) and sapele (ITTO 2022). Plywood exports are reported for ceiba, ofram and asanfena. There are several other West African species exported as veneer and plywood (Table 1) or manufactured into veneer and plywood in major importing countries (particularly China, India and Viet Nam) from imported logs.

4.2 Veneer and plywood sizes

Sliced face veneers for decorative purposes are commonly available in 0.5mm to 0.85mm thicknesses (nominal) with the most common sizes being 0.5mm to 0.6mm (Wagenführ *et al*. 2023). However, the possible range of sliced veneer thickness is greater and depends on the wood species and intended application. Flooring lamellas, for example, may require thicker sliced veneers which can be manufactured up to 2.5mm, 3.0mm or even 4.0mm thicknesses. For construction purposes, thicknesses of rotary cut veneers are usually 1.5 to 2.5mm (nominal sizes).

Plywood is produced in a number of sizes. Thicknesses range from 1.6mm to 76mm with the most common thicknesses in the 6.4mm to 19.0mm range. Although the core, crossbands and the face and back of a plywood sheet may be of different thicknesses, the thicknesses must balance around the middle core veneer. The most common size for plywood sheets used in building construction is 1200mm wide by 2440mm long.

Other common widths are 900mm and 1500mm. Lengths vary from 2400mm to 3600mm in 300mm increments, with special applications such as marine plywood requiring larger sheets.

In Malaysia, the most common sizes of plywood are 1200mm x 2440mm and 914mm x 1829mm with a 12mm thickness (Suffian *et al*. 2023). In the UK, the most common panel sizes are given as: 2440mm x 1220mm, 2440mm x 610mm, 2500mm x 1220mm, 3050mm x 1525 mm and 3050mm x 1220mm. The most common nominal thicknesses are: 3mm, 4mm, 6mm, 9mm, 12mm, 15mm, 18mm, 22mm, 25mm and 32mm (WPIF 2014).

Plywood for furniture end uses in Viet Nam are listed as 2.5mm to 25mm in thickness, in sizes 910mm x 1830mm, 1220mm x 2130mm, 1220 x 2440mm, and 1465 x 1110mm. The most common size is 1220mm x 2440mm. Construction plywood is commonly available in 5.2mm to 25mm thicknesses.

Indonesia has traditionally exported thin plywood (1.6mm to 8mm) although plywood is now available in a number of sizes, depending on the application.

Veneer sheets, Wood and Plywood Museum, Shinkiba Koto City Tokyo. Photo: JC Claudon/ITTO

5

Technical properties of tropical veneer and plywood

Plywood panels have significant bending strength both along and across the panel, with the differences in strength and stiffness along the panel length versus across the panel being much smaller than those differences in solid wood. Plywood also has excellent dimensional stability along its length and across its width. In contrast to MDF and particleboard, plywood has minimal irreversible thickness swelling in high moisture conditions. This attribute can be enhanced through the use of naturally durable species and waterproof gluelines. The alternating grain direction of its layers makes plywood resistant to splitting, allowing fasteners to be placed very near the edges of a panel (USDA 2010; Wagenführ *et al*. 2023).

Plywood is hygroscopic as it is a wood-based product, and its dimensions will therefore change in response to changes in humidity. Wood tends to shrink/expand much more across the grain than along the grain. However, the dimensional movement of plywood is limited by the cross-laminated veneer orientation because the longitudinal veneers in one ply tend to restrain the perpendicular veneers in the adjacent ply.

The physical and mechanical properties of plywood depend on the wood species (i.e. the density of wood used) and the quality of the veneer plies, type of adhesives used, thickness of the veneer, the number of plies, the temperature at which the veneer was dried, and the degree to which bonding conditions are controlled during production. The adhesive used to produce plywood primarily determines its resistance to climatic conditions. The durability of the adhesive-to-wood bond depends largely on the adhesive used but also on control of bonding conditions and on veneer quality. The grade of the panel depends upon the quality of the veneers used, particularly of the face and back.

Adhesive mixes in plywood manufacture consist of adhesives, extenders or fillers (designed to reduce the penetration of the adhesive away from the bond-line) and hardeners. Typical adhesive application quantities are 150-200g/m^2 per glueline (Wagenführ *et al*. 2023). The penetration behaviour of resins strongly depends on the molar masses present in the resin, with higher molar masses reducing wettability and impeding penetration into the wood surface. The penetration behaviour of resins into the wood surface also is influenced by various parameters such as wood species, amount of glue spread, press temperature, and pressure and hardening time. The temperature of the wood surface and of the glue line and hence the viscosity of the resin influences the penetration behaviour of the resin (Pizzi 2003). The wood moisture content influences several important processes such as wetting, flow of the adhesive, penetration into the wood surface, wood softening during compression, and hardening of the adhesive in the gluing and production of plywood. (Pizzi 2003).

Plywood strength is affected by the type of wood (wood species) and the veneer arrangement and thickness. Generally, plywood made with high density veneers has higher strength than plywood made with low density veneers.

6

Conversion factors for tropical veneer and plywood

6.1 Background on veneer and plywood density

As discussed in section 3, plywood can be used for a variety of construction and decorative end uses for internal or external use such as cladding, load-bearing componentry and furniture (Wagenführ *et al*. 2023; USDA 2010). An important feature of plywood is its relatively high mechanical strength to low weight ratio. Plywood weight and density depend on several factors such as the thickness of the glueline, the level of glue penetration into the veneer layers, the solids content of the glue, compression due to pressing and the density of the wood veneers (Bier 1986; Wagenführ *et al*. 2023; USDA 2010). Figure 1 shows basic density data for a number of species used in tropical veneer and plywood manufacture.

Figure 1: Wood basic densities for some wood species used in tropical veneer and plywood manufacture

Note: Basic density is the oven-dry weight of wood/green volume (wood only).The botanical names of the wood species listed, and some alternative common names, are given in Table 1.

The density of plywood is generally higher than that of the veneers used in its manufacture because in addition to veneer, it contains adhesives and additives such as industrial flour and anti-biodeterioration chemicals, and the boards have been compressed. The final amount of applied glue depends on the thickness of the glueline, and glue penetration into the veneer (Pizzi 1994). If the glue-line is too thick, then it can rupture under load but if it is too thin then bonding between veneer layers may not have taken place. Additionally, excessive glue absorption into each veneer can add extra cost and weight, but not enough glue can lead to poor veneer bonding and loss of strength (Pizzi 2003).

Glue uptake can generally differ for woods of differing basic density. Wood species with lower basic density generally have higher lumen porosity with less strength and can therefore take up more glue including from defects caused during veneer. In contrast, wood species with higher basic density generally have less voids and higher strength (Rijsdijk and Laming 1994; Mai and Militz 2023). However, reduced basic density also allows greater deformation during compression due to reduced strength (Wellons *et al.* 1983) thereby reducing porosity and glue uptake when cell collapse is created. Generally, all glue resin treatments increase the hardness (and therefore density) of wood as a result of glue uptake regardless of whether the resins are located in the cell wall or cell lumens (voids) (Mai and Militz 2023; Bier 1986; Suffian *et al.* 2023).

The moisture content of veneer in freshly produced plywood is typically in the range 7-10% to avoid steam blowouts during compression which typically occur above 13-14%. To achieve a moisture content range of 7-10% for the compressed plywood, veneer is usually dried to a level that takes into account moisture absorption from water-based resin glues (Wagenführ *et al.* 2023).

Plywood density D_p (kg/m^3) for equally dimensioned veneers of the same species can be estimated by adding the relative mass of all wood veneers (including final moisture content) and glue (final solids only) and compensating for compression volume change (Equation 1).

Equation 1

$$D_\rho = \frac{[(\rho\, t\, A\, n) + (Sc\, A\, (n-1))]}{n\, t\, A\, (1-CR)}$$

Where $\boldsymbol{\rho}$ = veneer density (kg/m^3); $\boldsymbol{t}$ = veneer thickness (m); $\boldsymbol{A}$ = veneer area (m^2); $\boldsymbol{n}$ = number of veneer layers; $\boldsymbol{S}$ = glue spread (kg/m^2); $\boldsymbol{c}$ = solids content fraction of the glue; $\boldsymbol{CR}$ = compression ratio. Note: The veneer area A is maintained for unit clarity.

The amount of compression can be described by the Compression Ratio (CR) (Equation 2) (Salca *et al* 2020; Bier 1986).

Equation 2

$$CR = \frac{(t_v - t_\rho)}{t_v}$$

Where t_v = the total thickness of all veneers (mm); t_p = the thickness of the plywood panel (mm)

Industrial and experimental CRs have been reported in the range 0.3% to 18.0% with a commonly used value around 10% (Bier 1986; Salca *et al.* 2020; Wang *et al.* 2006). The compression ratio is an important variable that can be manipulated to ensure plywood meets required standards. The final thickness of plywood also includes the thickness of the glueline which is generally negligible compared to the overall thickness. For example, Bier (1986) calculated a typical glueline thickness of 0.03mm for PF glue resin applied to 5-layer radiata pine plywood with nominal thickness 12 mm.

Glue application and glue solids content are two other important variables that can be manipulated to ensure plywood meets required standards. A general application range is 150-200 g/m^2 (Wagenführ *et al.* 2023). For example, a mean application for phenol formaldehyde, which is a widely used and fully exterior glue (USDA 2010; Krug *et al.* 2023) is 160 g/m^2 (Pot *et al.* 2016). The solids content of, for example, PF resin is in the order of 50%. (Wagenführ *et al.* 2023; Pizzi 1994).

The properties of plywood depend on the degree to which bonding conditions are controlled during production to meet standards specifications. Therefore, the CR, glue solids-content and glue application amount are generally reported as a range and can vary depending on specific plywood manufacturing processing conditions that are used to ensure that quality standards are met (USDA 2010; Pizzi 1994).

The density of each ply of wood veneer in a sheet of plywood depends on wood species, intrinsic wood properties, thickness, and level of defects such as knots. Veneer density is also affected by moisture content and in the absence of sufficient specific manufacturer data can theoretically be estimated from fundamental wood species information such as basic density, oven-dry density, maximum moisture content and shrinkage (Rijsdijk and Laming 1994; Maplesden and Pearson 2022). Knowledge of wood density can yield estimates of traded veneer density for a given moisture content. Plywood density can also be estimated for a given moisture content during manufacture provided layup species and thicknesses are known. Traded plywood moisture content is generally around 12% (dry basis) so the wood exists at a common average equilibrium moisture content and is unlikely to absorb or lose moisture before reaching its destination (USDA 2010). Research studies have also shown that, depending on the amount of adhesives and additives used, plywood densities are in the range of 16 to 30% higher than the density of the veneers used (Bier 1986; Suffian *et al.* 2023) and the number of layers of veneer does not significantly affect the density of the plywood (Suffian *et al.* 2023; Muhammad-Fitri *et al.* 2018).

Table 2 presents information from publications and trade websites on plywood densities by species or country. Although there are some variations for the same species (e.g. okoumé, eucalypts) there is significant variation in plywood densities between species. However, most of the estimates do not specify the plywood layups, or the species used as core veneer which is an important determinant of plywood density (see Section 6.3). In order to obtain more extensive data on plywood densities by species this study therefore derives theoretical plywood densities by species based on published wood water relationship information by species, and average plywood processing variables such as plywood compression ratios, glue application amount and solids content, for 5- and 7-layer plywood layups.

Table 2: Plywood densities by species/country source

Species/source	Plywood density (kg/m³)	Reference
all species	400-850	Niemz *et al.* 2023
all species	400-600	USDA 2010
all species	649	ITTO 2022
all species, construction grade	400-700	WPIF 2014
andoung	640	Rougier
batai	350	Muhammed-Fitri *et al.* 2017
Brazil plywood	470	FAO et al. 2020
combi species, 7-layer	510	Muhammed-Fitri *et al.* 2017
combi species, 5-layer	514	Muhammed-Fitri *et al.* 2017
combi-core	550-650	China Emberg
densified laminated plywood	800-1400	Niemz *et al.* 2023
eucalypts	724-744	Gaiotto *et al.* 1998
Eucalyptus grandis	600-618	Bal *et al.* 2014
Guyana plywood	764	FAO *et al.* 2020
hardwood faces, eucalypt core	580-600	China Emberg
Indonesia plywood	650	FAO *et al.* 2020
kelempayan	581	Muhammed-Fitri *et al.* 2017
kelempayan-batai	471	Muhammed-Fitri *et al.* 2017
kelempayan-eucalypts	645	Muhammed-Fitri *et al.* 2017
keruing	850	Mustard Construction
lauan	440	USDA 2010
Malaysia plywood	650	FAO *et al.* 2020
Mexico plywood	700	FAO *et al.* 2020
mixed light hardwoods (Malaysia average)	608	Suffian *et al.* 2023
okoumé	500	Rougier
okoumé	550+/-10%	Pipiska *et al.* 2023
ozigo	600	Rougier
pine	570-630	China Emberg
poplar	441-460	Bal *et al.* 2014
poplar	530-580	China Emberg
rubberwood	700-780	China Emberg
Uruguay plywood	545	FAO *et al.* 2020

Note: This table provides plywood densities presented in the listed publications and trade websites.

6.2 Methodology

Veneer and plywood conversion factors (m^3/1000 kg) estimated in this report were calculated from veneer and plywood density (kg/m^3) for species known to be traded as tropical veneer and traded or used in the manufacture of tropical plywood. Traded veneer density was assumed to be at 12% moisture content (dry basis) and veneer density used in plywood manufacture was assumed to be 8% moisture content (dry basis) after any moisture absorption during the manufacturing process. Plywood densities in this report assume plywood manufactured from veneers, and do not include blockboard or laminated veneer lumber (LVL).

If published data was not available, veneer densities at 8% and 12% moisture content were estimated from basic density, oven-dry density and volumetric shrinkage values using standard wood water relationship equations (Rijsdijk and Laming 1994; Maplesden and Pearson 2022). If discrepancies occurred between reported and calculated densities at 8% and 12% MC, the final density value was based on a calculation using basic density and volumetric shrinkage. This was because basic density and shrinkage can be obtained with relatively simple equipment, and is therefore more likely to be accurate, compared to specimens that require moisture equilibration at a specific temperature and humidity.

It was assumed that previously published sawnwood species information was representative of the same species when used for veneer and plywood calculations in this analysis (Maplesden and Pearson 2022).

Plywood density was calculated using Equation 1 and assumed that the glue used was phenol formaldehyde with a solids content of 50%, an application amount of 160 g/m^2 and CR of 10%. Phenol formaldehyde is one of the most common moisture-durable adhesives used in plywood and is commonly used for bonding softwood veneers. Urea formaldehyde (UF) is commonly used for bonding hardwood veneers, optimal glue bonding between the two glue types can be species specific (Aspari and Tanaka 2023; USDA 2010). Overall, however, PF resin is the more durable glue and is more typically used in layup schemes for tropical hardwood plywood which involve the gluing of both softwoods and hardwoods (USDA 2010; Mai and Militz 2023).

Veneer density calculations were performed for 60 tropical hardwood species commonly used in tropical plywood manufacturing, plus two core veneer species which were either a softwood (radiata pine) or were a non-tropical hardwood (poplar).

Thirty-six plywood layups using selected combinations from 16 different wood species were investigated in this study and are shown in Table 3 for 5- and 7- layer plywood. The 36 layup options represent the species components of most commonly produced tropical plywood including core veneer options of poplar and eucalypt, representing low- and high-density veneers respectively. Plywood density was also calculated for 5- and 7-layer plywood consisting entirely of these two core species alone for comparison (Appendix 1).

Two additional types of hardwood classifications were mixed medium hardwoods and mixed light hardwoods. Mixed medium hardwoods consisted of kelat, keruing and kapur species whilst mixed light hardwoods consisted of meranti-light red, meranti-dark red, rubberwood and nyatoh. Veneer density for these classifications was calculated by averaging the wood properties for each species within these two classifications.

6.3 Results

6.3.1 Tropical veneer density by species

Appendix 1 provides estimates by species of tropical veneer densities at 12% moisture content (MC), which is assumed to be the environment at the export transportation stage. This MC is less than the 20% MC required to avoid decay, and is the general MC required to allow stability of wood in average environmental conditions (USDA 2022; Wagenführ *et al.* 2023). These densities are used to derive the volume/weight conversion factors by species, as given in Appendix 1. Tropical veneer densities were highly variable for a standard 5-layer plywood layup and ranged from 363 kg/m^3 (sumauma) to 1052 kg/m^3 (kelat) and reflect the variation in wood basic densities, as shown in Figure 1. The corresponding volume/weight conversion factors for the two species listed ranged from 2.370 m^3/1000 kg to 0.849 m^3/1000 kg.

6.3.2 Tropical veneer area/volume conversions

Tropical veneer conversion from square metres to cubic metres can be estimated using the following formula:

Equation 3

$$V = t\,A$$

Where **V** = veneer volume (m^3); **t** = veneer thickness (m); **A** = veneer area (m^2).

Note: For tropical plywood with a thin decorative tropical veneer layer the average thickness is 0.5 mm (0.0005m).

6.3.3 Tropical plywood density by species

Appendix 1 provides theoretical estimates of plywood densities and volume/weight conversion factors for a standard 5-layer plywood layup (equivalent to the thicknesses specified in Table 3) using species which have been identified as being used in veneer and plywood manufacture. These estimates assume the same species throughout the panel. While some of these species are unlikely to be used in all-species plywood layups for economic reasons, it does indicate the significant variability in plywood densities which ranged from 422kg/m^3 to 1178kg/m^3 for the 5-veneer layup, and which are directly related to veneer densities. The mean plywood density for all species in Appendix 1 was 700 kg/m^3, although it is important to note that this figure does not represent the average density of tropical plywood produced and traded. The mean estimate for plywood densities compared with veneer densities (at 8% MC) was heavier per unit volume by 16% and ranged from 14-19%, which is in the range of previous studies which have used actual rather than theoretical data (Bier 1986; Suffian *et al.* 2023).

Table 3 presents the results of plywood density and conversion factors (volume/weight) for the 36 tropical plywood layups (5- and 7-layer) by species arrangement and veneer thickness. These layups represent several known species used in the manufacture of tropical plywood.

The results can be used to compare the impact of additional layers of veneer on board density, and the impact of the face/back veneers using a common core species, on board density. The results may be used to simplify theoretical calculations of tropical plywood densities.

Table 3: Tropical plywood densities and conversion factors for selected 5-ply and 7-ply plywood layups, by species and veneer thickness

Layup#	Species		Veneer thickness (mm)							Final board density (kg/m³)	Conversion factor (m³/ 1000 kg)
	core	face/back	face	core_1	core_2	core_3	core_4	core_5	back		
1	eucalypts	eucalypts	1.0	3.5	3.5	3.5	NA	NA	1.0	674	1.483
2	batai (albizia)	batai (albizia)	1.0	3.5	3.5	3.5	NA	NA	1.0	440	2.273
3	okoumé	okoumé	1.0	3.5	3.5	3.5	NA	NA	1.0	507	1.973
4	hevea (rubberwood)	hevea (rubberwood)	1.0	3.5	3.5	3.5	NA	NA	1.0	655	1.527
5	keruing	keruing	1.0	3.5	3.5	3.5	NA	NA	1.0	876	1.141
6	mixed light hardwoods	mixed light hardwoods	1.0	3.5	3.5	3.5	NA	NA	1.0	648	1.542
7	kadam	kadam	1.0	3.5	3.5	3.5	NA	NA	1.0	447	2.238
8	eucalypts	eucalypts	0.5	2.5	2.5	2.5	2.5	2.5	0.5	685	1.459
9	batai (albizia)	batai (albizia)	0.5	2.5	2.5	2.5	2.5	2.5	0.5	451	2.217
10	okoumé	okoumé	0.5	2.5	2.5	2.5	2.5	2.5	0.5	518	1.931
11	hevea (rubberwood)	hevea (rubberwood)	0.5	2.5	2.5	2.5	2.5	2.5	0.5	666	1.502
12	keruing	keruing	0.5	2.5	2.5	2.5	2.5	2.5	0.5	887	1.127
13	mixed light hardwoods	mixed light hardwoods	0.5	2.5	2.5	2.5	2.5	2.5	0.5	659	1.517
14	kadam	kadam	0.5	2.5	2.5	2.5	2.5	2.5	0.5	458	2.184
15	poplar	meranti	0.5	2.5	2.5	2.5	2.5	2.5	0.5	531	1.878
16	poplar	kapur	0.5	2.5	2.5	2.5	2.5	2.5	0.5	544	1.837
17	poplar	keruing	0.5	2.5	2.5	2.5	2.5	2.5	0.5	545	1.834
18	poplar	okoumé	0.5	2.5	2.5	2.5	2.5	2.5	0.5	518	1.931

Table 3: Tropical plywood densities and conversion factors for selected 5-ply and 7-ply plywood layups, by species and veneer thickness

Layup#	Species		Veneer thickness (mm)							Final board density (kg/m³)	Conversion factor (m³/ 1000 kg)
	core	face/back	face	core_1	core_2	core_3	core_4	core_5	back		
19	poplar	teak	0.5	2.5	2.5	2.5	2.5	2.5	0.5	537	1.864
20	poplar	bintangor	0.5	2.5	2.5	2.5	2.5	2.5	0.5	527	1.896
21	poplar	nyatoh	0.5	2.5	2.5	2.5	2.5	2.5	0.5	542	1.845
22	poplar	sapelli	0.5	2.5	2.5	2.5	2.5	2.5	0.5	536	1.865
23	poplar	mahogany	0.5	2.5	2.5	2.5	2.5	2.5	0.5	527	1.899
24	poplar	ozigo	0.5	2.5	2.5	2.5	2.5	2.5	0.5	542	1.846
25	poplar	andoung	0.5	2.5	2.5	2.5	2.5	2.5	0.5	529	1.889
26	eucalypts	meranti	0.5	2.5	2.5	2.5	2.5	2.5	0.5	686	1.455
27	eucalypts	kapur	0.5	2.5	2.5	2.5	2.5	2.5	0.5	699	1.430
28	eucalypts	keruing	0.5	2.5	2.5	2.5	2.5	2.5	0.5	700	1.428
29	eucalypts	okoumé	0.5	2.5	2.5	2.5	2.5	2.5	0.5	673	1.486
30	eucalypts	teak	0.5	2.5	2.5	2.5	2.5	2.5	0.5	692	1.446
31	eucalypts	bintangor	0.5	2.5	2.5	2.5	2.5	2.5	0.5	682	1.465
32	eucalypts	nyatoh	0.5	2.5	2.5	2.5	2.5	2.5	0.5	697	1.435
33	eucalypts	sapelli	0.5	2.5	2.5	2.5	2.5	2.5	0.5	691	1.447
34	eucalypts	mahogany	0.5	2.5	2.5	2.5	2.5	2.5	0.5	682	1.467
35	eucalypts	ozigo	0.5	2.5	2.5	2.5	2.5	2.5	0.5	697	1.435
36	eucalypts	andoung	0.5	2.5	2.5	2.5	2.5	2.5	0.5	684	1.461

Note: NA = not applicable; Meranti includes meranti, dark red; meranti red; meranti white; and meranti light red.Eucalypts include Eucalyptus grandis

The calculated plywood densities for single species 5-ply layups (Numbers 1-7) with face, core and back veneers of eucalypts, batai, okoumé, rubberwood, keruing, mixed light hardwoods and kadam, varied from 440 kg/m^3 (batai) to 876 kg/m^3(keruing) with a mean density of 607 kg/m^3 for all species. The corresponding 7-ply layups (Numbers 8-14) varied from 451 kg/m^3 (batai) to 887 kg/m^3 (keruing) with a mean density of 618 kg/m^3 for all species. The standard deviation (SD) for all densities for both 5- and 7-ply layups for single species was 155 kg/m^3, indicating the significant variation between species.

In the layups presented in Table 3, the number of layers did not significantly affect plywood density when the densities of the 5- and 7-layered plywood were compared for veneer layers of equal thickness. This finding has been observed in more comprehensive studies (Suffian *et al*. 2023; Muhammad-Fitri *et al*. 2018) and is logical because the number of gluelines is always one less than the number of veneers and the relative contribution to overall plywood density of the extra layer becomes less as the number of layers increase.

In the 7-ply layups with poplar cores and 11 different tropical hardwood face and back veneers (Numbers 15-25), there was minimal variation in plywood densities, which ranged from 518 kg/m^3 for poplar/okoumé, to 545 kg/m^3 for poplar/keruing, with a mean density of 534 kg/m^3 and SD of 9 kg/m^3. The eucalypt core/tropical hardwood face and back veneer layups (Numbers 26-36) varied from 673 kg/m^3 (eucalypt/okoumé) to 700 kg/m^3 (eucalypt/keruing), with a mean density of 689 kg/m^3 and SD of 9 kg/m^3. These relatively low SDs compared with the 100% veneer species layups indicates that, for the plywood layups shown, the density of the core veneers is a more important determinant of final board density than the face and back veneers.

6.4 Discussion

Tropical plywood manufacture in many manufacturing countries (particularly China) has transitioned to the use of more economic plantation raw materials in the non-visible core veneer layers. High costs of decorative tropical hardwood veneer have also led to thin veneers being increasingly used for face and back veneers which has been an issue for meeting quality standards (Parasar 2021). The density of plantation species (poplar, eucalypts, acacias, rubberwood, pine, etc.) used in tropical plywood cores has therefore become more important in determining tropical plywood weight/volume conversion factors than the density of the high-value tropical veneer faces which are typically used to describe tropical plywood products.

ITTO's standard conversion factor for plywood is 1.54m^3/1000kg and for veneer is 1.33m^3/1000kg. These relate to mean plywood densities of 649 kg/m^3 and 752 kg/m^3 respectively. The ITTO plywood conversion factor is in the density range of our calculations for 100% mixed light hardwoods (the major species used in Malaysian plywood) but is not in the density range of other species of plywood such as lower-density okoumé (the major species used in Gabon plywood), or poplar with tropical hardwood faces (the major species manufactured in China). As with tropical logs and sawnwood, the use of a "one size fits all" weight/volume conversion factor for all exporting countries can be improved with the species level data generated in this study when used with corresponding country export data at a species level.

However, accurate weight to volume conversion factor estimates by country for tropical veneer and plywood are unable to be determined in this study. In an earlier study, ITTO estimated weight to volume ratios for tropical logs and sawnwood by species, and by major tropical exporting country based on the weighted averages of the species exported (Maplesden and Pearson 2021). Weight to volume ratios for tropical veneer by species can be estimated from tropical species density data (Appendix 1) but there is limited export data on the species exported by country. This study has shown that estimates of tropical plywood weight to volume ratios can theoretically be determined by species, knowing the core species used in the plywood layups, along with veneer thickness, number of layers, glue solids and the compression ratio. However, this information is rarely available in entirety, because plywood is usually marketed as the species of the face veneer. As with tropical veneer, there is limited information on plywood species exported, and no information on the core veneers of plywood exported.

Although this study has not determined weight/volume conversion factors by country, a methodology and database has been developed which can be used to estimate conversion factors by country estimates when sufficient country export data by species is available.

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APPENDIX 1: Selected physical properties and volume: weight conversion factors for tropical veneer and plywood for selected wood species

Pilot (Trade Name)	Density (kg/m³) at 12% MC	Volumetric shrinkage (%)	Basic density	Fibre saturation point (%)	MAX MC (%)	Density (kg/m³) at oven-dry state	Density (kg/m³) at 8% MC	Veneer CF at 8% MC (m³/1000 kg)	Final plywood density (kg/m³)	Plywood CF (m³/1000 kg)
acacia	520	10.7	436	25	164.6	486	505	1.981	589	1.697
acajou d'Afrique	540	8.6	457	28	153.9	503	529	1.890	616	1.623
ako	456	12.4	380	28	198.2	434	450	2.224	528	1.894
andoung	590	10.8	486	28	140.9	545	568	1.761	659	1.516
aniégré	610	11.8	510	28	131.1	578	601	1.665	696	1.437
ayous	380	9.2	323	28	244.7	356	373	2.681	443	2.258
balau red	875	16.9	743	28	69.7	838	852	1.173	976	1.025
balau yellow	889	16.9	750	28	68.4	856	871	1.148	996	1.004
baromalli	679	17.5	550	28	116.9	667	676	1.478	780	1.282
batai	384	9.5	320	28	247.6	354	370	2.700	440	2.273
bintangor	564	9.4	471	28	147.4	520	545	1.836	634	1.578
cedro	555	10.3	465	28	150.1	518	541	1.847	630	1.587
essia	862	13.5	710	30	75.9	814	842	1.187	964	1.037
eucalypt *(E. deglupta)*	560	11.4	460	28	152.5	519	540	1.852	629	1.591
eucalypt *(E. saligna)*	930	11.4	779	28	63.4	879	915	1.093	1045	0.957
eucalypt *(E. grandis)*	586	15.5	480	28	143.4	568	581	1.720	674	1.483
eyong	789	11.5	660	28	86.6	746	776	1.289	890	1.123
gerutu	529	11.3	440	28	162.3	496	516	1.937	602	1.661
hevea	585	7.3	495	28	137.1	534	564	1.774	655	1.527
ilomba	542	12.8	450	28	157.3	516	534	1.873	622	1.608
ipê	975	13.2	819	28	57.2	907	937	1.067	1070	0.935
iroko	625	8.9	530	28	123.7	582	611	1.637	707	1.414
kadam	386	7.6	330	28	238.1	357	377	2.655	447	2.238
kapur	757	14.4	624	28	95.3	729	750	1.334	861	1.161
kedondong	529	11.5	435	28	164.9	491	511	1.957	596	1.677
kelat	1052	11.5	880	28	48.7	995	1034	0.967	1178	0.849
keruing	792	12.8	643	28	90.6	737	763	1.311	876	1.141
koto	658	15.0	540	28	120.3	635	652	1.535	752	1.329

Pilot (Trade Name)	Density (kg/m³) at 12% MC	Volumetric shrinkage (%)	Basic density	Fibre saturation point (%)	MAX MC (%)	Density (kg/m³) at oven-dry state	Density (kg/m³) at 8% MC	Veneer CF at 8% MC (m³/1000 kg)	Final plywood density (kg/m³)	Plywood CF (m³/1000 kg)
limba	507	10.8	431	28	167.1	470	490	2.041	573	1.745
mahang	391	4.8	340	28	229.2	357	380	2.631	451	2.219
mahogany	545	7.8	473	28	146.5	508	535	1.868	623	1.604
makore	726	10.8	610	28	99.0	684	713	1.402	821	1.218
medang	485	14.3	400	28	185.1	467	480	2.083	562	1.780
meranti, dark red	645	13.0	541	28	119.9	600	620	1.612	718	1.393
meranti, light red	480	14.3	402	28	183.8	449	462	2.165	542	1.847
meranti, red	620	13.3	523	28	126.3	593	612	1.633	709	1.411
meranti, white	720	7.7	579	33	107.8	627	664	1.507	766	1.306
meranti, yellow	637	10.4	540	25	120.3	603	627	1.596	725	1.38
merbau	838	7.8	719	28	74.1	765	806	1.240	924	0
mersawa	477	14.6	403	28	183.2	441	453	2.207	532	1.880
mixed light hardwoods: meranti-light red, meranti-dark red, hevea, nyatoh	566	10.5	478	28	155.1	535	558	1.792	644	1.554
mixed medium hardwoods: kelat, keruing, kapur	867	12.9	716	28	78.2	820	848	1.179	966	1.035
nyatoh	736	10.3	620	28	96.4	691	722	1.385	831	1.204
okoumé	443	11.3	367	28	207.5	414	431	2.322	507	1.973
onzambili	634	11.6	530	28	123.7	600	623	1.604	721	1.387
padauk amboina	593	6.7	515	28	129.2	552	584	1.713	677	1.477
pelong	606	10.4	510	28	131.1	569	594	1.682	689	1.451
pine, radiata pine	444	10.4	376	29	201.0	414	433	2.311	509	1.963
poplar	446	10.8	369	28	206.4	413	431	2.322	507	1.973
rengas	713	8.2	608	28	99.6	662	697	1.435	803	1.246
sapelli	690	14.0	574	28	109.3	633	652	1.534	753	1.329
sesendok	453	10.9	380	28	198.2	427	445	2.249	522	1.914
sipo	644	11.0	544	28	118.9	611	637	1.570	736	1.359
sozigo	728	14.0	600	28	101.7	700	720	1.389	829	1.207
sumauma	363	7.7	310	28	257.6	336	354	2.824	422	2.370

Pilot (Trade Name)	Density (kg/m^3) at 12% MC	Volumetric shrinkage (%)	Basic density	Fibre saturation point (%)	MAX MC (%)	Density (kg/m^3) at oven-dry state	Density (kg/m^3) at 8% MC	Veneer CF at 8% MC (m^3/1000 kg)	Final plywood density (kg/m^3)	Plywood CF (m^3/1000 kg)
teak	671	7.0	578	28	108.1	622	657	1.523	758	1.319
virola	506	13.7	408	28	180.2	473	487	2.052	570	1.754
wengé	918	8.7	766	28	65.6	839	882	1.134	1008	0.992
yemane	483	8.8	410	28	179	450	472	2.118	553	1.808

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Note:
MC= moisture content
FSP=fibre saturation point
CF=conversion factor
UF=urea formaldehyde
PF=phenol formaldehyde
See Table 1 for botanical names

International Tropical Timber Organization (ITTO)
International Organizations Center, 5th Floor, Pacifico Yokohama,
1-1-1 Minato-Mirai Nishi-ku, Yokohama, 220-0012 Japan
(T) +81-45-223-1110 (F) +81-45-223-1111
itto@itto.int www.itto.int