Journal of Tropical Forest Science 35(4): 417–428 (2023) *Ong CB et al.*
https://doi.org/10.26525/jtfs2023.35.4.417
ISSN: 0128-1283, eISSN: 2521-9847

ESTIMATION ON VOLUME-WEIGHTED AVERAGE WOOD DENSITY OF MALAYSIAN TIMBER FOR CALCULATION OF CARBON STOCK

Ong CB*, Khairul-Izzuddin H & Zairul AR

Forest Research Institute Malaysia, 52109 Kepong, Selangor, Malaysia

**ongcb@frim.gov.my*

Submitted November 2022; accepted February 2023

Wood density plays an important role in the calculation of national carbon stock, specifically when employing production approach to observe the carbon stock change based on national production of harvested wood products. Density is used as one of the parameter for estimating the carbon stock and annual carbon change in the harvested wood products pools. In this study, the commodity data, sawn timber productions from year 1995 to 2020, were gathered from published annual statistics by Forestry Statistics Peninsular Malaysia. These data include all the commercial timbers in Peninsular Malaysia, which are grouped according to trade names. Efforts were made to correctly identify and compile the botanical name as well as density range and mean of each timber trade name according to published references. Basic density and total volume of sawn timber productions were used to calculate the weighted average wood density of Malaysian timber. The estimated volume-weighted average wood density (563 kg m^{-3}) was comparable to the arithmetic mean (559 kg m^{-3}) and published density value for tropical species (590 kg m^{-3}) by Intergovernmental Panel on Climate Change 2006.

Keywords: Harvested wood products, carbon stock, sawn timber, trade name

INTRODUCTION

Harvested wood products are products manufactured from wood-based materials harvested from the forests. The carbon absorbed by the forests will remain stored in the harvested wood product and is taken into account in the estimation of carbon stock. Wood products play an important role in the declaration of national carbon stock, and subsequently contribute to the fight against climate change by acting as a carbon storage pool in the country. The carbon storage pool can be increased by encouraging the use of harvested wood products to substitute the use of products made from energy-intensive materials such as steel, concrete, or plastics. Examples of harvested wood products are wooden components in building, furniture, paper and plywood. Tsunetsugu and Tonosaki (2010) indicated that increasing the use of harvested wood products may result in the realisation of a low-carbon society. They also stated that utilisation of harvested wood products has two substitution effects, namely contributing to energy saving by substituting energy-intensive materials with harvested wood products and reducing carbon dioxide emission from fossil fuel burning by substituting with bioenergy sources, specifically wood-based materials from sustainable forest management.

There are many approaches for accounting harvested wood products in the carbon stock change within a country. One of them is the production approach which estimates the changes in carbon stock of harvested wood products using data from the producing country (IPCC 2006, Tsunetsugu & Tonosaki 2010). This approach takes into account the carbon stocks in the forest and harvested wood products pool. It does not include the effect from imported wood and only data from domestically produced wood is used. Hence, it is important for a country to have related activity data of the domestically produced wood, specifically data from the country's sawn timber productions, in the estimation of harvested wood products carbon pool. One of the parameters needed to estimate the harvested wood product pool is the density of timber species (IPCC 2006, Fujiwara et al. 2007). In most situations, wood density data for each forest species are not always available. There are also situations where trees to be harvested are not identified to the species level during the prefelling inventory process. Therefore, it is best to estimate a weighted average wood density based on volume and density of known species, using an arithmetic mean or midrange value (Brown 1997).

This paper presents an estimation of volume-weighted average density for Malaysian timber species based on sawn timber productions data collected from the year 1995 to 2020 in Peninsular Malaysia. The estimated volume-weighted average density will be useful in the future calculation of carbon stock and carbon change of the harvested wood products pool in the country. Yearly sawn timber productions (in volume m^3) were gathered from the Forestry Statistics Peninsular Malaysia for the year 1995 to 2020 (JPSM (1995 to 2020)). More than 140 timber groups/trade names were listed together with the yearly sawn timber productions in this database. According to Wong et al. (2019), over 3000 timber-sized species have been recorded in Malaysia and almost all of them have internationally-recognised botanical names. These timber species are also given vernacular names by local natives, timber trade names by timber traders and standardised Malaysian names. Some timber species do not have vernacular names, while some timber species have multiple vernacular names given by the various natives when identifying trees in their respective localities. Trade names were used by the timber traders to group timbers with similar properties so that they can be marketed using a single trade name. This eases the trading activities since it reduces the large number of timber names, if each species is to have different individual name. There are also Association of South East Asian (ASEAN) standard names, where common timbers between ASEAN countries are given equivalent timber names, with the intention of minimising confusion due to different national timber names; and enhancing marketing and trading of timber between the countries (Ong et al. 2019). Standardised timber names are also important to avoid confusions and mistakes when estimating contribution of harvested wood product in the reporting of carbon storage and subsequent carbon dioxide emissions or removals, specifically when using country-specific data. Vieilledent et al. (2018) emphasised the importance of using the correct species names for estimation of conversion factor in the calculation of basic wood density of tree using global wood technology database.

MATERIALS AND METHODS

It is important to correctly identify and regroup the timber trade names gathered from the sawn timber statistics. All names were checked and regrouped accordingly using the information in A Dictionary of Malaysian Timbers (Wong et al. 2019) as reference. The compiled timber groups, botanical names, densities and total sawn timber productions from year 1995 to 2020 are presented in Table 1. Some of the timber names were updated to the most recent spelling, namely chengal, bruas, chempedak, chempedak air, mesepat, meranti bumbong, meranti langgong, meranti pa'ang, rambutan pachat and sesendok. Some of the names were not found in Wong et al. (2019), thus they were grouped accordingly such as rengas pacat (rengas) and meranti daun (meranti daun besar). Efforts were also made to identify the botanical names of the timbers in the list. Botanical names are important to accurately determine the density of the timbers. The records in Identification and Properties of Malaysian Timbers (Lim et al. 2016) and Wong et al. (2019) were used as references. For instance, durian hutan is categorised as durian (standard Malaysian names) as well as being identified as *Durio oxleyanus* (botanical name). In this study, *D. oxleyanus* with mean density of 610 kg m^{-3} was used and not durian (*Durio* spp.) which comprises multiple species with density range of 420-685 kg m^{-3}. Nevertheless, durian was also recorded in the sawn timber statistics with total production of 1 m^3 only, thus, it was grouped together with durian hutan. Most of the timbers have high volume of total productions except for some timbers such as kandis or bruas (7 m^3), meranti temak (6 m^3), putat (48 m^3), sena (19 m^3) and sentang (50 m^3). All these timbers were still included in the calculation of the weighted average density of Malaysian timbers.

Most of the timbers have vernacular names originated from the native language of a specific region. Standard Malaysian names such as jati (teak) and kayu getah (rubberwood), were added into this compilation, providing better comprehension. The sawn timber statistics categorised most of the timbers into one of these groupings, namely heavy hardwoods (HHW), medium hardwoods (MHW) and light hardwoods (LHW). Table 2 shows the classifications according to the Malaysian Grading Rules for Sawn Hardwood Timber (MTIB 2009). This

Table 1 Timber group, botanical name, density and total sawn timber production from year 1995 to 2020

Timber group	Botanical names	Midrange density (kg m^{-3})	Mean density (kg m^{-3})	Calculated basic density (kg m^{-3})	Total sawn timber production (m^3)	References
Akasia, *Acacia mangium*	*Acacia* spp., *Acacia mangium*	565	623	505	454,137	Mohamad-Omar & Mohd-Jamil (2011)
Ara, Jejawi, Kelepong	*Ficus* spp.	493	445	405	2020	Lim et al. (2004)
Balau, Balau bukit, Balau laut, Damar laut	*Shorea* spp., *S. foxworthyi*, *S. lumutensis*	960	960	750	1,427,314	Lopez (1983a)
Balau merah/ Red balau, Balau membatu, Membatu	*Shorea* spp., *S. collina*, *S. guiso*	840	-	665	325,847	Lopez (1981c)
Batai	*Albizia* spp., *Paraserianthes falcataria*	385	-	320	13,341	Wong (2019)
Bekak	*Aglaia* sect. *Amoora*	824	768	613	12,760	Lim et al. (2016)
Berangan	*Castanopsis* spp.	794	-	632	16,444	-
Bintangor	*Calophyllum* spp.	665	640	518	609,304	Abdul-Rashid (1984)
Bitis	*Madhuca utilis*, *Palaquium ridleyi*, *P. stellatum*	970	-	757	8686	Lim (1989)
Chengal/ Cengal	*Neobalanocarpus heimii*	903	945	740	588,139	Lopez (1983b)
Damar hitam	*Shorea multiflora*	653	-	527	312,250	-
Damar minyak	*Agathis* spp.	465	440	364	92,577	Lim et al. (2016) Wong (1981a)
Dedali	*Strombosia javanica*	648	-	524	54,832	-
Durian, Durian hutan	*Durio* spp., *D. oxleyanus*	658	610	495	718,784	Lim et al. (2016)
Durian daun	*Durio lowianus*	645	-	521	10,499	Wong & Lim (1990)
Geronggang	*Cratoxylum* spp.	480	481	396	176,026	Ani (1987)
Gerutu	*Parashorea* spp.	705	-	566	341,145	Choo & Lim (1986a)
Giam	*Hopea* spp.	1043	975	761	52,982	Lim (1984a)
Jati/ Teak	*Tectona grandis*	680	-	548	15,137	Wong (2019)
Ketapang, Jelawai	*Terminalia* spp.	618	-	501	15,427	Wong (2019)
Jelutong	*Dyera* spp.	460	435	360	392,233	Ser (1981a)
Kandis, Bruas/ Beruas	*Garcinia* spp., *G. hombroniana*	905	-	711	7	Wong (2019)
Kapur, Keladan	*Dryobalanops* spp., *D. oblongifolia*	695	800	636	1,237,789	Ser (1981b)

continued

Table 1 Continued

Timber group	Botanical names	Midrange density (kg m^{-3})	Mean density (kg m^{-3})	Calculated basic density (kg m^{-3})	Total sawn timber production (m^3)	References
Kasah	*Pterygota* spp.	715	670	540	1670	Lim et al. (2016)
Kasai	*Pometia* spp.	808	-	641	419,102	Lim (1984b)
Kayu getah/ Rubberwood	*Hevea brasiliensis*	565	640	518	3,083,991	MTIB & FRIM (1988)
Kedondong, Kedondong bulan	Spp. of Burseraceae, *Canarium littorale*	735	620	503	3,312,926	Ahmad-Shakri (1983)
Kekabu, Kekabu hutan	*Bombax* spp., *Bombax valetonii*	480	465	383	62,393	Zainuddin (1985)
Kekatong	*Cynometra* spp.	978	1010	785	158,721	Mohd-Shukari (1983)
Kelat, Kelat merah	*Syzygium* spp., *S. chlorantha*	758	-	605	5,456,181	Lim (1984c)
Keledang, Chempedak/ Cempedak, Chempedak ayer/ Cempedak air	*Artocarpus* spp.	720	720	577	484,273	Lopez (1984a)
Kelempayan	*Neolamarckia cadamba*	418	380	316	1560	Mohamad-Omar et al. (2020)
Kembang semangkok	*Scaphium* spp.	635	-	514	741,777	Lim (1987)
Kempas	*Koompassia malaccensis*	945	890	701	3,010,333	Ser (1981c)
Keranji	*Dialium* spp.	1003	-	780	866,179	Ani & Lim (1990)
Keruing	*Dipterocarpus* spp.	845	800	636	3,775,175	Choo & Sim (1981)
Kulim	*Scorodocarpus borneensis*	808	835	661	338,240	Abdul-Rashid (1983)
Kungkur	*Albizia splendens*	658	-	531	18,610	Ani & Lim (1991)
Ludai	*Sapium* spp.	378	402	334	5849	Lim et al. (2016)
Machang	*Mangifera* app.	738	730	585	44,498	Lopez (1982a)
Mahang, Kubin, Mesepat/Mersepat	*Macaranga* spp., *M. gigantea, M. conifera*	383	-	318	205	Wong (2019)
Mata ulat	*Kokoona* spp.	975	-	761	69,107	Wong (1982)
Medang	Spp. of Lauraceae	600	-	487	1,912,411	Wong (2019)
Melantai, Meranti melantai	*Shorea* spp., *S. macroptera*	520	-	426	513,932	Wong (2019)
Melembu	*Pterocymbium* spp.	465	465	383	584	Lim et al. (2016)
Melunak	*Pentace* spp.	643	655	529	592,388	Ho (1983)
Mempening	*Lithocarpus* spp., *Quercus* spp.	793	-	630	8326	Wong (2019)
Mempisang	spp. of Annonaceae	663	-	535	110,781	Lim (1988)
Mengkulang	*Heritiera* spp.	760	721	578	613,775	Lopez (1981a).
Meranti bakau	*Shorea uliginosa*	675	-	544	303,882	Wong (2019)
Meranti bukit/ Dark red meranti	*Shorea platyclados*	688	739	591	213,171	Lim et al. (2016)

continued

Table 1 Continued

Timber group	Botanical names	Midrange density (kg m^{-3})	Mean density (kg m^{-3})	Calculated basic density (kg m^{-3})	Total sawn timber production (m^3)	References
Meranti bumbung/ White meranti	*Shorea dealbata*	720	720	577	568	Lim et al. (2016)
Meranti daun besar/ Light red meranti	*Shorea hemsleyana*	760	789	628	3031	Lim et al. (2016)
Meranti jerit/ White meranti	*Shorea henryana*	944	944	739	611	Lim et al. (2016)
Meranti kuning/ Yellow meranti	*Shorea spp.*	655	670	540	694,834	Choo & Lim (1988)
Meranti langgong/ Light red meranti	*Shorea lepidota*	498	-	409	4947	Choo & Lim (1983)
Meranti merah muda/ Light red meranti	*Shorea* spp.	633	545	445	136,213	Lim et al. (2016)
Meranti merah tua/ Dark red meranti, Meranti merah	*Shorea* spp.	665	700	562	9,741,795	Lim et al. (2016)
Meranti nemesu	*Shorea pauciflora*	685	706	567	224,414	Lim et al. (2016)
Meranti pa'ang/ paang	*Shorea bracteolate*	600	624	506	81,976	Lim et al. (2016)
Meranti paya/ Light red meranti	*Shorea platycarpa*	658	690	555	4380	Lim et al. (2016)
Meranti pipit/ White meranti	*Shorea assamica* subsp. *globifera*	576	576	469	18,272	Lim et al. (2016)
Meranti putih/ White meranti	*Shorea* spp.	752	670	540	588,027	Choo & Lim (1986b)
Meranti rambai daun/ Light red meranti	*Shorea acuminata*	588	-	478	12,972	Choo & Lim (1983)
Meranti sarang punai/ Light red meranti	*Shorea parvifolia*	545	-	445	567,504	Choo & Lim (1983)
Meranti sengkawang merah/ Dark red meranti	*Shorea singkawang*	693	690	555	11,095	Lim et al. (2016)
Meranti seraya, Seraya/ Dark red meranti	*Shorea curtisii*	693	657	530	588,913	Lim et al. (2016)
Meranti temak/ White meranti	*Shorea hypochra*	696	736	589	6	Lim et al. (2016)
Meranti tembaga/ Light red meranti	*Shorea leprosula*	550	-	449	999,040	Choo & Lim (1983)
Merawan	*Hopea* spp.	712	-	571	883,228	Ho (1981)
Merbatu	*Atuna* spp., *Kostermanthus* spp., *Licania* spp., *Maranthes corymbosa*, *Parinari* spp.	843	-	667	99,585	Wong (2019)
Merbau	*Intsia* spp.	778	800	636	1,272,004	Ser (1982)
Merpauh, Merpauh periang, Periang	*Swintonia* spp., *S. schwenkii*	760	755	603	855,249	Sim (1984)
Mersawa	*Anisoptera* spp.	655	-	529	1,240,609	Lopez (1981b)
Mertas	*Ctenolophon parvifolius*	865	-	683	4656	Wong (2019)

continued

Table 1 Continued

Timber group	Botanical names	Midrange density (kg m^{-3})	Mean density (kg m^{-3})	Calculated basic density (kg m^{-3})	Total sawn timber production (m^3)	References
Nyalin/ Minyak berok	*Xanthophyllum* spp.	840	795	632	5374	Lim & Gan (2008)
Nyatoh	*Madhuca* spp., *Palaquium* spp., *Payena* spp.	660	-	533	1,867,034	Wong (1981b)
Pauh kijang	*Irvingia malayana*	1090	1135	871	71,570	Zaitun (1985)
Palajau/ Pelong	*Pentaspadon* spp.	658	-	531	101,307	Wong (2019)
Penaga	*Mesua ferrea*	1065	-	823	87,083	Wong (2019)
Penarahan	Spp. of Myristicaceae	570	593	482	135,475	Mohd-Shukari (1984)
Perah	*Elateriospermum tapos*	985	-	768	414,850	Wong (2019)
Perupok	*Lophopetalum* spp.	560	-	457	23,516	Wong (1983)
Petai	*Parkia* spp.	615	-	499	560	Ahmad-Shakri (1984)
Petaling	*Ochanostachys amentacea*	953	-	745	5554	Wong (2019)
Podo/ Podo cucur atap	*Dacrycarpus imbricatus*	650	-	525	172	Wong (2019)
Pulai	*Alstonia* spp.	433	400	332	11,413	Sim (1982)
Punah	*Tetramerista* spp.	713	720	577	23,953	Lopez (1982b)
Punggai	*Coelostegia griffithii*	-	705	566	12,349	Lim et al. (2016)
Putat	*Barringtonia* spp.	648	-	523	48	Wong (2019)
Rambutan pachat/ pacat	*Xerospermum* spp.	960	-	750	327	Wong (2019)
Ramin, Ramin melawis	*Gonystylus* spp., *G. bancanus*	658	675	544	401,534	Sim (1983)
Rengas, Rengas pacat	*Gluta* spp., *Melanochyla* spp.	800	800	637	189,254	Lopez (1984b)
Resak	*Cotylelobium* spp., *Vatica* spp.	938	-	734	326,916	Lim (1982a)
Sena	*Pterocarpus indicus*	625	625	506	19	Sim (1988)
Sentang	*Azadirachta excelsa*	665	618	536	50	Lim et al. (2006)
Sepetir	*Copaifera palustris*, *Sindora* spp.	658	675	544	478,173	Ho (1982)
Sesendok/ Sesenduk	*Endospermum* spp.	480	400	332	165,718	Mohd-Shukari (1982)
Simpoh	*Dillenia* spp.	748	735	588	416,779	Lim (1982b)
Surian	*Toona* spp.	400	416	345	14,181	Mohd-Shukari (1985)

continued

Table 1 Continued

Timber group	Botanical names	Midrange density (kg m^{-3})	Mean density (kg m^{-3})	Calculated basic density (kg m^{-3})	Total sawn timber production (m^3)	References
Tembusu	*Cyrtophyllum* spp., *Picrophloeus* spp., *Utania* spp.	858	-	677	1714	Wong (2019)
Tempinis	*Streblus elongatus*	970	-	757	850	Wong (2019)
Terap	*Artocarpus* spp., *Parartocarpus* spp.	480	496	407	8267	Tan & Lim (1989)
Terentang	*Campnosperma* spp.	440	432	358	68,109	Grewal (1986)
Tualang	*Koompassia excelsa*	833	880	694	1,182,305	Ser (1984)
Tulang daing	*Callerya atropurpurea*	705	-	566	3501	Wong (2019)
Other HHW	-	960	-	750	1,387,786	Wong (2019)
Other MHW	-	800	-	636	4,368,927	Wong (2019)
Other LHW, Selambor, Hujan-hujan	-	560	-	457	9,070,662	Wong (2019)
Others, Kayu jaras	-	560	-	457	4,593,116	Wong (2019)
				Grand total	76,607,051	

Table 2 Air-dry density ranges of timber groups (MTIB 2009)

Timber group	Air-dry density at 15% moisture content (kg m^{-3})
Heavy hardwoods	800 to 1120
Medium hardwoods	720 to 880
Light hardwoods	400 to 720

classification is based on the density of timber at 15% moisture content and its natural durability when exposed to Malaysian condition. The sawn timber statistics also listed the groupings of "other heavy hardwoods", "other medium hardwoods" and "other light hardwoods". These groups represent other lesser-known timbers and they are also included in the calculation of the weighted average density. The midrange density of these timber groups were calculated using the density range given in Table 2. Another category listed in the Malaysian Grading Rule is softwood, where only three timber trade names were listed as commercial Malaysian timber, namely damar minyak, podo and sempilor. In the sawn timber statistics, only damar minyak and podo are listed. The statistics records also listed imported timbers such as hard maple, maple, pine, red oak and mahogany. The total sawn timber productions of these imported timbers were not used in this study. The timbers selambor (141 m^3) and hujan-hujan (61 m^3) were listed in the sawn timber statistics as light hardwoods but they were not found in the references. Thus, these timbers were grouped as "other light hardwoods" in this study. One of the timbers with high production volume is kayu jaras (4,586,089 m^3). Kayu jaras is defined as small diameter logs with diameter of less than 150 mm and does not differentiate between timber species. These small-diameter logs are often obtained from clear-felling activities including from alienated lands. They are considered as poles and often used as fuelwood, materials for minor constructions and pilings. In this study, kayu jaras is grouped with another category of timber in the sawn timber statistics, named "others" (7027 m^3). Assumptions were made that this "others" category consists of timbers that were not identified or unpopular, and the total production volume is small compared to other timber groups. Since the species of timber groups kayu jaras and "others" are unknown, the midrange density of light hardwoods was used in the study, assuming that the density of small-diameter logs is inherently low. Better species identification of kayu jaras will improve the descriptions of this group and future inclusion of densities from medium hardwoods and heavy hardwoods in the determining the weighted average density of Malaysian timber. For example, one of the commonly sourced kayu jaras is mangrove logs (Mohd-Jamil & Amir 2022). Mangrove logs are called bakau (standard Malaysian name, vernacular name) which consist of timbers from the genus *Bruguiera*, *Ceriops* and *Rhizophora*, as well from the species *Kandelia candel*. Bakau timber has high density with the range of 630–1170 kg m^{-3} (Wong et al. 2019) which is higher than light hardwoods 400–720 kg m^{-3}).

Density

Efforts were made to identify the mean density of the timbers using information from A Dictionary of Malaysian Timbers (Wong et al. 2019), Identification and Properties of Malaysian Timbers (Lim et al. 2016), and Timber Trade Leaflet series as well as other related references. Table 1 lists the references used in obtaining the mean density of the timbers. Density range was taken mainly from Lim et al. (2016) whenever mean density was not available. Density range is stated in most of the publications because many of the genus consisted of multiple species. For example, gerutu is the standard Malaysian name for genus of *Parashorea*. This genus comprises of species *Parashorea stellata Kurz* (air-dry density range 640–680 kg m^{-3}; mean density 675 kg m^{-3}); *P. densiflora* (air-dry density range 600–800 kg m^{-3}; mean density 675 kg m^{-3}); and *P. globosa* (air-dry density range 575–670 kg m^{-3}; mean density 645 kg m^{-3}) (Choo & Lim 1986a). Understandably, density range is used to represent the genus. The midrange density ρ_{MR} (kg m^{-3}) of each timber was calculated simply based on the equation 1.

$$\rho_{MR} = \frac{\rho_{MR} - \rho_{Min}}{2} \quad (1)$$

where, ρ_{Max} = maximum value of density (kg m^{-3}) and ρ_{Min} = minimum value of density (kg m^{-3}).

Table 1 shows the timber's midrange density as well as the mean density. The mean density and density range gathered from the references were from timbers in air-dry condition, specifically timber with moisture content of approximately 15%. For example, the mean density of *Acacia mangium* (673 kg m^{-3}) was taken from the study by Mohamad-Omar & Mohd-Jamil (2011), which 20-year-old *Acacia mangium* from plantation trees, were tested in dry condition (mean moisture content 15.8%). Wood density in Malaysia is commonly reported in air-dry condition. This air-dry density is defined as the mass of wood at 15% moisture content divided by its volume at the same moisture content. The following formula is used to calculate density ρ_M (kg m^{-3}) of wood at moisture content M (%) (ASTM 2014):

$$\rho_M = \frac{m_M}{v_M} \quad (2)$$

where m_M = mass (kg) of wood at moisture content M (%) and V_M = volume (m^3) of wood at moisture content M (%)

Although air-dry density is commonly used in Malaysia and other tropical Asia and Africa countries, wood densities for tropical American timbers are reported as basic wood density. Intergovernmental Panel on Climate Change (IPCC 2006) displayed the list of timber species with their corresponding basic wood density as data source in the calculation of weighted average wood density value. Basic wood density (kg m^{-3}) can be estimated from the oven-dry mass of timber and its green volume (ASTM 2014):

$$\rho_b = \frac{m_0}{v_{Max}} \quad (3)$$

where m_0 = oven-dry mass (kg) of wood and v_{Max} = green volume (m^3) of wood.

Assuming that fibre-saturation of wood is 30% moisture content, density of wood at moisture content below the fibre-saturation point can be estimated from the basic density using the following formula (ASTM 2014):

$$\rho_M = \frac{\rho_b(1+0.01M)}{1-0.009(30-M)\frac{\rho_b}{\rho_w}} \quad (4)$$

where ρ_M = density at moisture content M below fibre-saturation point (kg m^{-3}), ρ_b = basic density (kg m^{-3}), M = moisture content (%) of wood and ρ_w = density of water (approximately 1000 kg m^{-3}).

The basic density can be calculated by rearranging equation 4:

$$\rho_b = \frac{\rho_M}{(1+0.01M)+0.009(30-M)\frac{\rho_M}{\rho_w}} \quad (5)$$

Table 1 shows the calculated values of basic density using the mean density or midrange density of timber at 15% moisture content. The midrange density was used when the mean density was not available.

Volume-weighted Average Wood Density

The volume-weighted average wood density of Malaysian timber was estimated using values in Table 1 and was calculated based on the equation below (Brown 1997):

$$\rho_{WA} = \left(\frac{V_1}{V_t}\right)\rho_1 + \left(\frac{V_2}{V_t}\right)\rho_2 + \cdots + \left(\frac{V_n}{V_t}\right)\rho_n \quad (6)$$

where ρ_{WA} = volume-weighted average wood density (kg m^{-3}), V_1, V_2, ... V_n = production volume of timber group 1, 2, … to the nth group (m^3), V_t = total production volume of sawn timber from year 1995 to 2020 = 76,607,051 m^3 and ρ_1, ρ_2, ρ_n = wood density of timber group 1, 2, ... to the nth group (kg m^{-3}).

Arithmetic Mean Wood Density

The arithmetic mean wood density was calculated using the midrange and mean density values in Table 1 and was based on the equation below:

$$\rho_{AM} = \frac{\rho_1 + \rho_2 + \cdots + \rho_n}{n} \quad (7)$$

where ρ_{AM} = arithmetic mean wood density (kg m^{-3}), ρ_1, ρ_2, ρ_n = wood density of timber group 1, 2, ... to the nth group (kg m^{-3}) and n = number of timber groups.

RESULTS AND DISCUSSION

Table 3 shows the arithmetic mean and volume-weighted average wood density of Malaysian timber species. The arithmetic mean was calculated by dividing the total air-dry density of the timber groups with the number of groups as shown in equation 7. The densities were from the mean density and the midrange density of the timber groups. Midrange density was used whenever mean density was not available. The volume-weighted average wood density was calculated with the inclusion of total sawn timber productions from year 1995 to 2020 using equation 6.

The results showed that the arithmetic means of air-dry density and basic density were lower but near to the respective volume-weighted average density. In comparison with the default values from IPCC (2006), which indicated that the basic density of tropical species is 0.59 oven-dry tonne m^{-3} (590 kg m^{-3}), the calculated volume-weighted average density (basic density) for Malaysian timber was lower but still closely similar with less than 5% difference. IPCC (2006) stated that the default basic density of the tropical species was calculated by averaging the density values (arithmetic means) of its listed species. This average value was used as default factors in the conversion from product units to carbon (IPCC 2006), which includes materials such as roundwood, industrial roundwood, sawnwood,

Table 3 Arithmetic mean and volume-weighted average density of Malaysian timber species calculated using values from air-dry density and basic density

	Arithmetic mean density (kg m^{-3})	Volume-weighted average density (kg m^{-3})
Air-dry density at 15% moisture content	699	703
Basic density	559	563

other industrial roundwood, pulpwood, chips, particles, wood fuel and wood residues. A study by Reyes et al. (1992) found that the mean basic density of tropical timber species in Asia was 0.57 g cm^{-3} (570 kg m^{-3}). As many as 428 species from the tropical Asia region were used in the estimation, which include data from Malaysia, Sri Lanka and tropical forest regions of east India. The finding was close to the basic density values estimated in this study, where 111 timber groups were used.

From the 111 timber groups in this study, a total of 59 mean densities and 52 midrange densities were used in the estimation of both the arithmetic and volume-weighted average densities (Table 1). Mean density is always preferable than midrange density because midrange density is very sensitive to outliers since it takes only two extreme (lowest and highest) data points in the calculation. Nevertheless, comparison between the 59 mean densities with the corresponding midrange densities showed values which are close to each other. Only some timber groups showed high percentage differences between mean density and midrange density, such as '*Acacia mangium*, Akasia' (10% difference), 'kapur, keladan' (14%), rubberwood (12%), 'kedondong, kedondong bulan' (17%), light red meranti (15%), white meranti (12%) and sesendok (18%). The high percentage differences for timber groups '*Acacia mangium*, Akasia', rubberwood and sesendok may be due to the fact that these species are plantation species. The high variations in density are due to the different maturities or ages of timber from the harvested trees as well as the present of different clones in the plantation (Lim & Gan 2000, Lim et al. 2003, Lim et al. 2011, Hamdan et al. 2015). For timber groups 'kapur, keladan' (density range 575–815 kg m^{-3}), 'kedondong, kedondong bulan' (495–975 kg m^{-3}), light red meranti (380–885 kg m^{-3}), and white meranti (512–992 kg m^{-3}), the high variations were contributed by the big gap in the density range as well as the many species within the respective genus, especially kedondong (37 species), light red meranti (11 species) and white meranti (10 species) (Lim et al. 2016).

CONCLUSION

In this study, volume-weighted average density of Malaysian timber species was estimated using sawn timber production statistics from the year 1995 to 2020. This density is pertinent in the estimation of carbon stock in the harvested wood products pool. Efforts were also made to gather sawn timber production statistics from the year before 1995 but the data were not segregated according to species. Future improvements to the estimated density values can be made to include more data describing the mean density of timber species and not the midrange density. It would also be useful to segregate all the timber groups into individual species with their respective density. Unfortunately, it is impossible due to the way data collections of the sawn timber productions were made, where timber trade names were used and not based on their botanical names. Nevertheless, the estimated volume-weighted average density (basic density 563 kg m^{-3}) of Malaysian timber species in this study was close to the IPCC's published value (basic density kg m^{-3}) for tropical species.

REFERENCES

Abdul-Rashid AM. 1983. *Malaysian timbers – kulim*. Trade Leaflet No. 77. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Abdul-Rashid AM. 1984. *Malaysian timbers – bintangor*. Trade Leaflet No. 89. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Ahmad-Shakri MS. 1983. *Malaysian timbers – kedondong*. Trade Leaflet No. 73. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Ahmad-Shakri MS. 1984. *Malaysian timbers – petai*. Trade Leaflet No. 85. Malaysian Forest Service. Malaysian Timber Industry Board & Forest Research Institute Malaysia, Kuala Lumpur.

Ani S. 1987. *Malaysian timbers – geronggang*. Timber Trade Leaflet No. 104. Malaysian Timber Industry Board & Forest Research Institute Malaysia, Kuala Lumpur.

Ani S & Lim SC. 1990. *Malaysian timbers – keranji*. Timber Trade Leaflet No. 112. Malaysian Timber Industry Board & Forest Research Institute Malaysia, Kuala Lumpur.

ANI S & Lim SC. 1991. *Malaysian timbers – kungkur*. Timber Trade Leaflet No. 114. Malaysian Timber Industry Board & Forest Research Institute Malaysia, Kuala Lumpur.

ASTM D2395-14. 2014. *Standard test methods for density and specific gravity (relative density) of wood and wood-based materials*. American Society for Testing and Materials, ASTM International, Pennsylvania.

Brown S. 1997. *Estimating Biomass and Biomass Change of Tropical Forests: A Primer* (Vol. 134). Food & Agriculture Organisation (FAO), Rome.

Choo KT & Sim HC. 1981. *Malaysian timbers – keruing*. Trade Leaflet No. 48. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Choo KT & Lim SC. 1983. *Malaysian timbers - light red meranti*. Malaysian Forest Service Trade Leaflet No. 75. Malaysian Timber Industry Board & Forest Research Institute Malaysia, Kuala Lumpur.

Choo KT & Lim SC. 1986a. *Malaysian timbers – gerutu.* Timber Trade Leaflet No. 101. Malaysian Timber Industry Board & Forest Research Institute Malaysia, Kuala Lumpur.

Choo KT & Lim SC. 1986b. *Malaysian timbers – white meranti.* Timber Trade Leaflet No. 102. Malaysian Timber Industry Board & Forest Research Institute Malaysia, Kuala Lumpur.

Choo KT & Lim SC. 1988. *Malaysian timbers – yellow meranti.* Timber Trade Leaflet No. 107. Malaysian Timber Industry Board & Forest Research Institute Malaysia Kuala Lumpur.

Fuijwara T, Yamashita K & Kuroda K. 2007. Basic densities as a parameter for estimating the amount of carbon removal by forests and their variation. *Bulletin-Forestry And Forest Products Research Institute Ibaraki*, 6: 215.

Grewal GS. 1986. *Malaysian timbers – terentang.* Timber Trade Leaflet No. 103. Malaysian Timber Industry Board & Forest Research Institute Malaysia, Kuala Lumpur.

Hamdan H, Anwar UMK & Mahmudin S. 2015. Properties and utilization of sesenduk for value-added products. *Proceedings of the Forest Products Seminar. FRIM Proceedings No. 6.* Forest Research Institute Malaysia, Kepong.

Ho KS. 1981. *Malaysian timbers – merawan.* Trade Leaflet No. 53. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Ho KS. 1982. *Malaysian timbers – sepetir.* Trade Leaflet No. 60. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Ho KS. 1983. *Malaysian timbers – melunak.* Trade Leaflet No. 80. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

IPCC. 2006. *The Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories*, The National Greenhouse Gas Inventories Programme. Eggleston HS et al. (eds) Institute for Global Environmental Strategies, Hayama.

JPSM. 1995 to 2020. *Forestry Statistics Peninsular Malaysia.* Jabatan Perhutanan Semenanjung Malaysia, Kuala Lumpur.

Lim SC. 1982a. *Malaysian timbers – resak.* Trade Leaflet No. 62. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Lim SC. 1982b. *Malaysian timbers – simpoh.* Trade Leaflet No. 67. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Lim SC. 1984a. *Malaysian timbers – giam.* Trade Leaflet No. 84. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Lim SC. 1984b. *Malaysian timbers – kasai.* Trade Leaflet No. 92. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Lim SC. 1984c. *Malaysian timbers – kelat.* Trade Leaflet No. 88. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Lim SC. 1987. *Malaysian timbers – kembang semangkok.* Timber Trade Leaflet No. 105. Malaysian Timber Industry Board and Forest Research Institute Malaysia, Kuala Lumpur.

Lim SC. 1988. *Malaysian Timbers – mempisang.* Timber Trade Leaflet No. 106. The Malaysian Timber Industry Board and Forest Research Institute Malaysia, Kuala Lumpur.

Lim SC. 1989. *Malaysian Timbers – bitis.* Timber Trade Leaflet No. 110. The Malaysian Timber Industry Board and Forest Research Institute Malaysia, Kuala Lumpur.

Lim SC & Gan KS. 2000. Some physical properties and anatomical features of 14-year-old *Acacia mangium. Journal of Tropical Forest Products* 6: 206–213.

Lim SC & Gan KS. 2008. *Identification and utilization of lesser-known commercial timbers in Peninsular Malaysia 10: meraga, merbau kera, merbau lalat and minyak berok.* Timber Technology Bulletin No. 46. Forest Research Institute Malaysia, Kepong.

Lim SC, Gan KS & Choo KT. 2003. *The characteristics, properties and uses of plantation timbers - rubberwood and Acacia mangium.* Timber Technology Bulletin No. 26. Forest Research Institute Malaysia, Kepong.

Lim SC, Gan KS & Choo KT. 2004. *Identification and utilization of lesser-known commercial timbers in Peninsular Malaysia 1: ara, bangkal, bebusok and bekoi.* Timber Technology Bulletin No. 29. Forest Research Institute Malaysia, Kepong.

Lim SC, Gan KS & Khairul A. 2006. *Timber of sentang.* Timber Technology Bulletin No. 38. Forest Research Institute Malaysia, Kepong.

Lim SC, Gan KS & Tan YE. 2011. *Properties of Acacia mangium Planted in Peninsular Malaysia. ITTO Project on Improving Utilization and Value Adding of Plantation Timbers from Sustainable Sources in Malaysia.* Forest Research Institute Malaysia, Kepong.

Lim SC, Nordahlia AS, Abd Latif M et al. 2016. *Identification and Properties of Malaysian Timbers. Malaysian Forest Records.* No. 53. Forest Research Institute Malaysia, Kepong.

Lopez DT. 1981a. *Malaysian timbers – mengkulang.* Trade Leaflet No. 47. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Lopez DT. 1981b. *Malaysian timbers – mersawa.* Malaysian Forest Service Trade Leaflet No. 56. The Malaysian Timber Industry Board and Forest Research Institute Malaysia, Kuala Lumpur.

Lopez DT. 1981c. *Malaysian timbers – red balau.* Malaysian Forest Service Trade Leaflet No. 45. The Malaysian Timber Industry Board and Forest Research Institute Malaysia, Kuala Lumpur.

Lopez DT. 1982a. *Malaysian timbers – machang.* Trade Leaflet No. 68. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Lopez DT. 1982b. *Malaysian timbers – punah.* Trade Leaflet No. 59. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Lopez DT. 1983a. Malaysian timbers – balau. Trade Leaflet No. 78. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Lopez DT. 1983b. Malaysian timbers – chengal. Trade Leaflet No. 72. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Lopez DT. 1984a. Malaysian timbers – keledang. Trade Leaflet No. 91. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Lopez DT. 1984b. Malaysian timbers – rengas. Trade Leaflet No. 87. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Mohamad-Omar MK & Mohd-Jamil AW. 2011. Mechanical properties. In Lim SC et al. (eds) *Properties of Acacia mangium Planted in Peninsular Malaysia. ITTO Project on Improving Utilization and Value Adding of Plantation Timbers from Sustainable Sources in Malaysia.* Forest Research Institute Malaysia, Kepong.

Mohamad-Omar MK, Mohd-Jamil AW & Khairul M. 2020. Mechanical properties. In Roszaini K et al. (eds) *Kelempayan Wood - Properties and Uses. FRIM Research Pamphlet* No. 144. Forest Research Institute Malaysia, Kepong.

Mohd-Jamil AW & Amir SK. 2022. *Glossary of terminologies of Malaysian timber species and groups.* FRIM Timber Technology Bulletin No. 114. Forest Research Institute Malaysia, Kuala Lumpur.

Mohd-Shukari M. 1982. *Malaysian timbers – sesendok.* Trade Leaflet No. 66. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Mohd-Shukari M. 1983. *Malaysian timbers – kekatong.* Trade Leaflet No. 79. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Mohd-Shukari M. 1984. *Malaysian timbers – penarahan.* Trade Leaflet No. 90. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Mohd-Shukari M. 1985. *Malaysian timbers – surian.* Trade Leaflet No. 93. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur

MTIB. 2009. *The Malaysian Grading Rules for Sawn Hardwood Timber.* Malaysian Timber Industry Board, Kuala Lumpur.

MTIB & FRIM. 1988. Malaysian timbers – rubberwood. Timber Trade Leaflet No. 58. Malaysian Timber Industry Board & Forest Research Institute Malaysia.

Ong CB, Nordahlia AS, Lim SC & Gan KS. 2019. *Equivalent Timber Names in ASEAN. FRIM Timber Technology Bulletin No. 95.* Forest Research Institute Malaysia, Kepong.

Reyes G. 1992. *Wood densities of tropical tree species. Volume 88.* US Department of Agriculture, Forest Service, Southern Forest Experiment Station, North Carolina.

Ser CS. 1981a. *Malaysian timbers – jelutong.* Trade Leaflet No. 55. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Ser CS. 1981b. *Malaysian timbers – kapur.* Trade Leaflet No. 46. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Ser CS. 1981c. *Malaysian timbers – kempas.* Trade Leaflet No. 44. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Ser CS. 1982. *Malaysian timbers – merbau.* Trade Leaflet No. 65. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Ser CS. 1984. *Malaysian timbers – tualang.* Trade Leaflet No. 83. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Sim HC. 1982. *Malaysian timbers – pulai.* Trade Leaflet No. 64. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Sim HC. 1983. *Malaysian timbers – ramin.* Trade Leaflet No. 74. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Sim HC. 1984. *Malaysian timbers – merpauh.* Trade Leaflet No. 82. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Sim HC. 1988. *Malaysian timbers – sena.* Timber Trade Leaflet No. 108. Malaysian Timber Industry Board & Forest Research Institute Malaysia, Kuala Lumpur.

Tan YE & Lim SC. 1989. *Malaysian timbers – terap.* Timber Trade Leaflet No. 109. Malaysian Timber Industry Board & Forest Research Institute Malaysia, Kuala Lumpur.

Tsunetsugu Y & Tonosaki M. 2010. Quantitative estimation of carbon removal effects due to wood utilization up to 2050 in Japan: effects from carbon storage and substitution of fossil fuels by harvested wood products. *Journal of Wood Science* 56: 339–344. https://doi.org/10.1007/s10086-009-1107-4.

Vieilledent G, Fischer FJ, Chave J et al. 2018. New formula and conversion factor to compute basic wood density of tree species using a global wood technology database. *American Journal of Botany* 105: 1653–1661. https://doi.org/10.1002/ajb2.1175.

Wong TM. 1981a. *Malaysian timbers - damar minyak.* Timber Trade Leaflet No. 43. The Malaysian Timber Industry Board and Forest Research Institute Malaysia, Kuala Lumpur.

Wong TM. 1981b. *Malaysian Timbers - nyatoh.* Trade Leaflet No. 54. Malaysian Forest Service. Malaysian Timber Industry Board & Forest Research Institute Malaysia, Kuala Lumpur.

Wong TM. 1982. *Malaysian timbers - mata ulat.* Trade Leaflet No. 70. Malaysian Forest Service. Malaysian Timber Industry Board & Forest Research Institute Malaysia, Kuala Lumpur.

Wong TM. 1983. *Malaysian timbers – perupok.* Trade Leaflet No. 76. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.

Wong TM, revised by Lim SC, Gan KS & Chung RCK. 2019. *A Dictionary of Malaysian Timbers* (3rd Edition). Malayan Forest Records No. 30. Forest Research Institute Malaysia, Kepong.

Wong WC & Lim SC. 1990. *Malaysian timbers – durian.* Timber Trade Leaflet No. 113. Malaysian Timber Industry Board and Forest Research Institute Malaysia, Kuala Lumpur.

Zainuddin MY. 1985. *Malaysian timbers – kekabu.* Trade Leaflet No. 98. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur

Zaitun S. 1985. *Malaysian timbers – pauh kijang.* Trade Leaflet No. 99. Malaysian Forest Service. Malaysian Timber Industry Board, Kuala Lumpur.