Assessment of the Carbon Footprint of Rubberwood Sawmilling in Peninsular Malaysia: Challenging the Green Label of the Material

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Rubberwood is an important wood resource for the wood-based industry in Malaysia and the neighboring countries in the Southeast Asian region. Many studies have been conducted to assess rubberwood's properties and economic viability for value-added wood products manufacturing. However, information on the material's environmental performance and green labeling is limited. Therefore, the life cycle approach was carried out in this study to evaluate the carbon footprint of rubberwood rough green sawn timber production. A cradle-to-gate approach was applied. The results indicated that the carbon footprint for rubberwood rough green sawn timber production was 52.9 CO_2-eq/m^3. However, when taking into consideration the carbon footprint of the whole rubberwood sawmilling industry in comparison to the Dark Red Meranti sawmilling industry, it is apparent that the total carbon footprint of the rubberwood sawmilling industry is remarkably higher. This is due to the use of inefficient processing technology, which leads to a high level of wastage on the harvesting site and in the mill. Therefore, this study shows that the green label accorded to rubberwood appears questionable from the perspective of its carbon footprint, and that efforts must be taken to minimize the waste if the material is to achieve a green material status.

Keywords: Carbon footprint; Life cycle; Sawmilling; Rubberwood; Green material

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INTRODUCTION

In Malaysia, the commercial cultivation of rubberwood (*Hevea brasiliensis*) for natural rubber or latex production began at the turn of the last century. As the trees reached an age of over 25 years the latex production decreased and the old mature trees were felled and replanted. These felled trees produced a substantial amount of wood material, up to 0.1 m^3 per tree, which at that point in time had very little commercial value and was either used as fuel or discarded as waste.

It was not until the mid-1970s that the commercial potential of rubberwood was fully exploited through the extensive research, development, and marketing efforts of the Malaysian Timber Industry Board (MTIB) and the Forest Research Institute of Malaysia (FRIM). In fact, Teoh *et al.* (2011) reported that rubberwood became an important alternative source of sawn timber when the government implemented controlled-logging in the natural forests in line with the Sustainable Forest Management (SFM) principles in the early 1980s. This consequently reduced the supply of logs to the sawmilling industry.

In essence, the commercial success of rubberwood took almost seven decades to be understood in a market environment that has been dominated by well-established wood species from the natural forests (Balsiger *et al.* 2000).

Currently, an application for rubberwood has been found in almost all sectors of the wood products industry such as construction, secondary remanufactured wood products, composite-panels, decorative, *etc*. (Teoh *et al.* 2011). Moreover, rubberwood has emerged as the most important furniture raw material not only in Malaysia, but also in Indonesia and Thailand, which all boast substantial rubber cultivation areas. Apart from being a plantation tree crop with a befitting theme of "from waste to wealth," rubberwood also has excellent aesthetic appeal with its yellowish color, excellent working properties, and its comparable mechanical properties with other established furniture wood materials such as Oak (*Quercus* sp.), Beech (*Fagus* sp.), Kembang Semangkok (*Scaphium* sp.), Meranti (*Shorea* sp.), and Nyatoh (*Palaquium* sp.). To overcome the "waste-wood perception" of rubberwood, the government undertook concerted marketing efforts to boost the material's perception in the global market by rebranding and renaming it as "Malaysian Oak." Despite such extensive public-relation efforts, the success of rubberwood as a furniture material has been attributed primarily to its low cost and environmental friendliness (Ratnasingam *et al.* 2012).

Teoh *et al. (*2011) reported that since the early 2000s, rubberwood-sawn timber enjoyed a strong demand in the domestic market and in the regional markets, while the supply of traditional wood resources from the natural forests reduced steadily. Noor Aini *et al.* (2014) reported that a quota system was subsequently imposed in Malaysia, which ensured that only limited quantities of rubberwood-sawn timber could be exported out the country, further guaranteeing a sufficient supply for domestic needs. It has been reported that the total amount of rubberwood-sawn timber produced in the Southeast Asian region accounted for almost 8 million m^3 in 2015. Nearly 85% of this amount was contributed by Malaysia, Thailand, and Indonesia (Teoh *et al.* 2011).

It is undeniable that the commercial exploitation of rubberwood in the wood-based industry has made significant socio-economic contributions to the country (Shigematsu *et al.* 2011; Teoh *et al.* 2011; Ratnasingam *et al.* 2012). Although several studies have evaluated the socioeconomic perspectives of the rubberwood industry and the long-term economic potential of the tree crop to the Southeast Asian region, reports on the environmental value of rubberwood utilization are non-existent (Balsiger *et al.* 2000; Norini *et al.* 2009; Shigematsu *et al.* 2011; Teoh *et al.* 2011; Ratnasingam *et al.* 2012; Noor Aini *et al.* 2014). A critical issue gaining significant attention is the release of anthropogenic emission during the mobile-sawmilling activities extensively used in the rubberwood industry, which consequently impacts the environment.

Several studies have indicated that the consumption of resources, namely material, energy, and water during the conversion of saw-logs into sawn timber also leads to an environmental impact. However, Eshun *et al.* (2010) underlined that the environmental impacts are generally different between countries and sawmills due to differences in technologies, environmental standards, and procedures. Nevertheless, the most common environmental impact is global warming, which results from the emission of carbon dioxide in large quantities along with other gases such as methane (CH_4) and nitrous oxide (N_2O). These greenhouse gases (GHGs) lead to rising global temperatures and can be assessed mathematically, which is expressed as a carbon dioxide equivalent (CO_2-eq). This calculation and conversion of GHGs into CO_2-eq is described as a carbon footprint, which is an important attribute of the environmental friendliness of the material.

Against these considerations, research on the environmental performance of rubberwood-sawn timber production is of high interest. Therefore, a preliminary study of the carbon footprint of the rubberwood sawmilling activity was performed through application of the life cycle assessment (LCA) technique. In this study, the GHGs emissions from rubberwood sawn timber production were converted to CO_2-eq for the purpose to assess the carbon footprint. The LCA approach can be used to assess the environmental performance due to resources consumption in a production activity (Azapagic 1999; Rebitzer *et al.* 2004; Straka and Layton 2010). The life cycle perspective has emerged to be extensively employed by manufacturers, governments, and businesses to observe and attend to environmental issues. The findings of this study will establish benchmark values for the rubberwood sawmilling industry in the context of its environmental profile, which will contribute towards the overall environmental improvement of the rubberwood industry.

EXPERIMENTAL

Description of the System in the Study

The carbon footprint assessment (global warming potential) concentrated on the production of rubberwood rough green sawn timber in Peninsular Malaysia. There were 128 rubberwood sawmills involved in the assessment of the carbon footprint. The life cycle assessment (LCA) approach was applied in this study, as it is the most widely used technique to evaluate a carbon footprint (Milota *et al.* 2005; Bergman and Bowe 2012; Ratnasingam *et al.* 2015). The standard and guidelines for the standardization of the carbon footprint was performed in compliance with the ISO/TS 14067 (2013).

System Boundary

The system boundary reflects the flow of the resources, the production of outputs, and environmental emissions during the rubberwood-sawn timber production (Bergman and Bowe 2012). In this study, the assessment of the carbon footprint was accounted on the life cycle stage of cradle-to-gate, specifically from the transportation of the saw-logs to the sawmills until the production of rubberwood rough green sawn timber (Fig. 1). The activity covered the haulage of saw logs from the rubber plantations in Peninsular Malaysia to the sawmills. Diesel-powered lorries were used to transport rubberwood saw logs from the rubber plantations to the sawmills. The lorry used for hauling the saw logs belonged to the owner of the sawmills.

Because rubberwood saw logs are susceptible to fungal attack, all of the rubberwood saw logs that reached the sawmills were stored in heated water ponds prior to the sawing process. The storage of rubberwood saw logs was in the period of seven to ten days, depending on the readiness for sawing. Purchased electricity and rubberwood waste (sawdust and splinters) were used to heat up the water in the ponds. The average temperature of the water in the ponds was 30 ºC. A front-end loader was then used to carry the saw logs from the log yard to the sawmill site. The sawing transformed the saw logs into rough green sawn timber. The dimensions of the sawn timber depended on the customers' demand. Prior to packaging for shipment, the green sawn timber was moved to the storage area, where it was arranged and stacked according to various sizes.

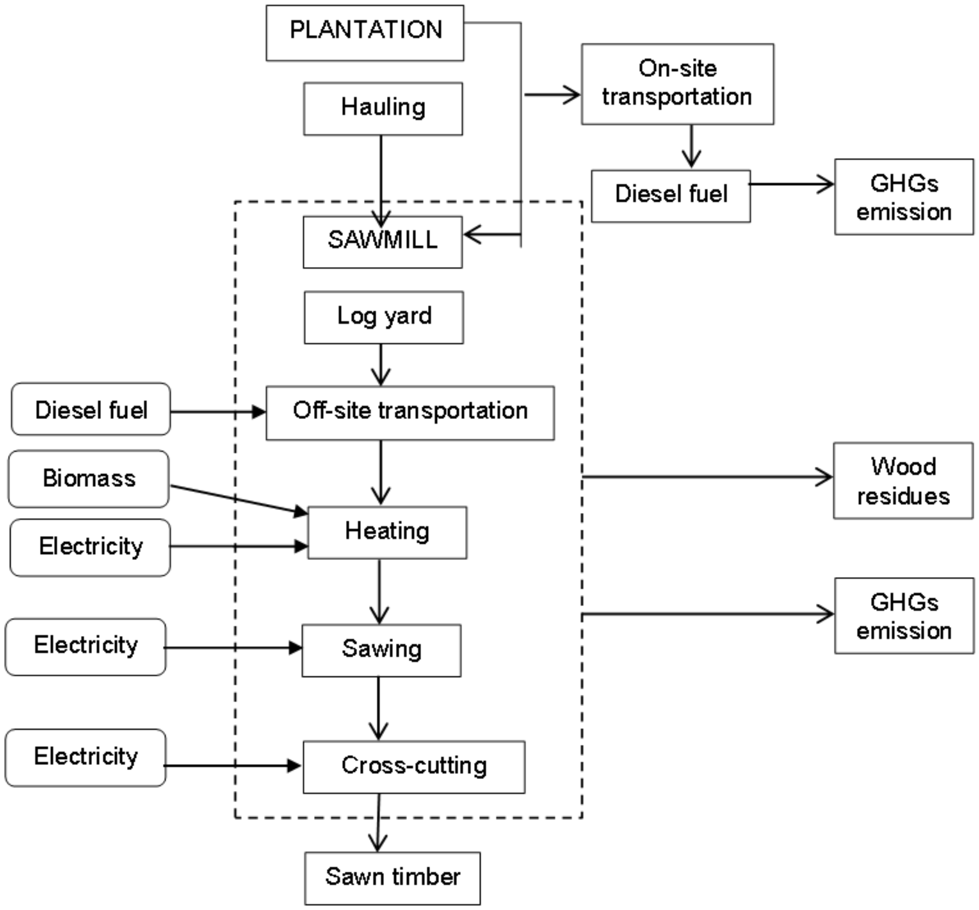

Fig. 1. System boundaries of rubberwood-sawn timber production

Functional Unit

The standard ISO/TS 14067 (2013) describes a functional unit as the quantified performance of a product system, which performs as a reference unit. According to Martínez-Alonso and Berdasco (2015), the functional unit is used for comparison with other materials. In this study, the investigated finished product was rubberwood rough green sawn timber and the measurement unit for sawn timber was volume (Milota *et al.* 2005; Bergman and Bowe 2012; Ramasamy *et al.* 2015). Therefore, the functional unit was standardized as per-unit volume basis for 1.0 m^3 of rubberwood rough green sawn timber.

Data Collection

The study accounted for the amount of rubberwood-sawn logs (obtained from Peninsular Malaysia) used and the energy inputs during the manufacturing process of rough green sawn timber. The assessment period of material flow and energy consumption during the manufacturing processes was carried out throughout the year of 2015

Inventory assessment

The inventory data used in this study was comprised of activity data and an emission factor (Eq. 1). The activity data, which was related to the on-site measurement of electrical energy consumption and diesel fuel consumption during the sawmilling activity, was collected and compiled from the sawmills. The breakdown of the fossil fuels used to generate sawmill electricity was in accordance with the 2014 data, as reported by the Malaysia Energy Information Hub Unit (2016). Coal, gas, petroleum, diesel, hydro, and other renewable energy sources were enumerated as 43.20%, 43.80%, 0.90%, 2.0%, 9.6%, and 0.5%, respectively. Meanwhile, the emission factor represented the factor value of the GHGs emission, which was comprised of contributions from CO_2, CH_4, and N_2O obtained from the International Panel of Climate Change (2013).

$$GHGs\ emission\ (kg) = Activity\ data \times emission\ factor\ GHGs\ emission \quad (1)$$

Impact assessment

Each of the GHGs, emission was translated into a carbon footprint with an equivalency factor of CO_2-eq according to Eq. 2. The equivalency factors for CO_2, CH_4, and N_2O were 1, 25, and 298, respectively. The global warming potential of 100 years was applied in this study in compliance with the IPCC (2013) guidelines.

$$Carbon\ footprint\ (kg\ CO_{2\text{-}eq}) = GHGs\ emission \times Equivalency\ factor \quad (2)$$

RESULTS AND DISCUSSION

The findings, with regard to the carbon footprint of rubberwood rough green sawn timber production from 128 sawmills in Peninsular Malaysia, are presented in this section. The Forestry Department of Peninsular Malaysia (FDPM) licensed the rubberwood sawmills in operation throughout the year 2015. For records and tax assessment, the production data were extracted from the weekly production return reports submitted by each of the sawmills and reported to the FDPM. The carbon footprint output was analysed on the basis of the mean values of kg CO_2-eq per m^3 of rubberwood rough green sawn timber.

Product Yield

The flow of rubberwood saw logs in the manufacturing process produced rubberwood rough green sawn timber as the main product. The average annual production of rubberwood rough green sawn timber was 131,000 m^3 per sawmill, while the efficiency of rubberwood sawmilling was tracked through its recovery. According to Bergman and Bowe (2012), sawmills are usually concerned with the recovery factor. In this present study, the average recovery of rubberwood rough green sawn timber was 27%. This suggested that rubberwood sawmilling has very low recovery. Ratnasingam *et al.* (2013) explained that the through and through sawing technique applied to saw rubberwood logs often resulted in the low recovery of rubberwood-sawn timber due to the small diameter of rubberwood saw logs in comparison to saw logs from a natural forest. Furthermore, the rubberwood saw logs also had a comparatively higher degree of tapering and internal stresses, which impaired the sawing recovery (Ratnasingam and Scholz 2009).

Wood losses in the form of off-cuts, sawdust, and splinters were enumerated during the conversion of rubberwood logs into rough green sawn timber. The largest quantity of the co-products produced during the sawmilling activity was off-cuts (72%), followed by splinters (0.5%), with the remainder as sawdust (0.2%). The survey for 128 sawmills indicated that off-cuts were sold, while the sawmills used splinters and sawdust for fuel generation. The remaining 20% of the splinters was landfilled.

Energy Consumption

Sawmilling itself consumed energy in the form of electricity and diesel fuel. Prior to the sawing and crosscutting processes, electrical energy was used to heat up the water during the rubberwood log storage. The average amount of electrical energy consumed was 21.06 kWh for 1 m^3 of rubberwood rough green sawn timber. The proportion of electrical energy used in steaming, sawing, and crosscutting was 30.72%, 66.20%, and 3.08%, respectively. Meanwhile, diesel fuel was used for the haulage and off-road transportation activities only. The average consumption of diesel fuel for the haulage of the saw logs to the sawmills was 0.296 L/m^3 per km, while the off-road transportation consumed an average of 0.093 L/m^3 diesel fuel to carry the logs and sawn timber boards within the mill site. The inventory data of electrical energy and diesel fuel consumption is shown in Table 1.

Table 1. Energy Consumption during Rubberwood-sawn Timber Production

Activity		Energy	Consumption	Unit
Haulage	Transportation of logs to mills	Diesel	0.30	L/m^3
Sawmill processing	Steaming	Electricity	6.47	kwh/m^3
	Sawing		13.94	
	Cross-cutting		0.65	
Off-road transportation	Transportation of logs and sawn timber within mills	Diesel	0.09	L/m^3

Carbon Footprint Assessment

The implication of resources consumption was investigated in terms of a carbon footprint. It was noticeable from previous studies that GHGs were discharged during the consumption of electrical energy and diesel fuel energy during manufacturing activities (Milota *et al.* 2005; Bergman and Bowe 2012; Ratnasingam *et al.* 2015). A similar finding was also observed in this study. The primary sources of electrical energy generation in Malaysia are fossil fuels. The fossil fuels discharged GHGs in varying quantities. A likely explanation was given by Saidur *et al.* (2007) that fossil fuels are composed of carbon, sulphur, nitrogen, and other GHG related compounds. The combustion of diesel fuel also releases GHGs as well.

Similar to fossil fuels and diesel fuel, wood also stores carbon. Generally, wood is characterized as an environmentally friendly material due to its potential to store carbon during its conversion to end-products (Martínez-Alonso and Berdasco 2015; Ratnasingam *et al.* 2015). In contrast, the loss of wood during the production processes was accounted as carbon loss. Nonetheless, the release of CO_2 from burning or decomposition was accounted as biogenic CO_2. According to Bergman and Bowe (2012), biogenic CO_2 is also known as carbon neutral because the CO_2 released to the environment during the burning or decomposition of wood is reabsorbed during the growth of the tree. Muñoz *et al.* (2013) pointed out that wood or biomass is normally assigned a global warming potential of 0 because wood does not theoretically contribute to the carbon footprint.

The cradle-to-gate assessment of rubberwood rough green sawn timber production showed that the mean total GHGs emission was 52.9 kg CO_2-eq/m^3. The proportion of the carbon footprint between the electricity and diesel fuel consumption is shown in Fig. 2. It appeared that the use of electricity was more responsible for the release of GHGs to the environment, amounting to 98.0% of the release.

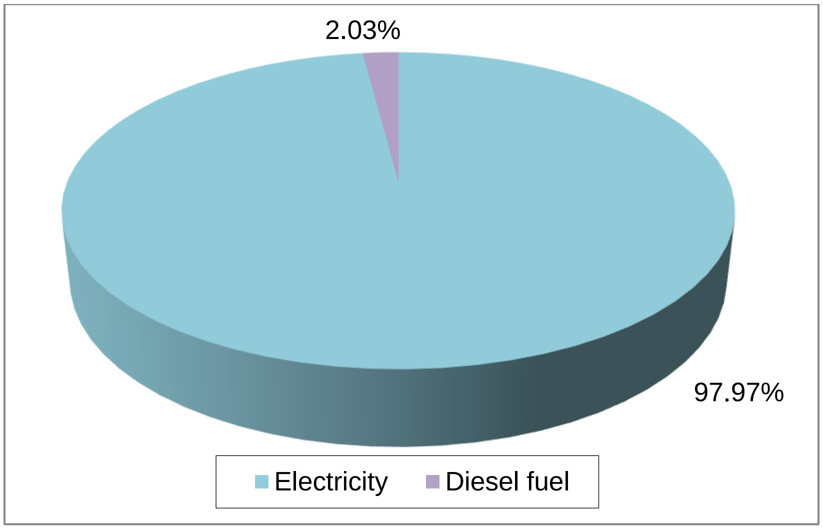

Fig. 2. The proportion of carbon footprint from energy consumption

Haulage

Based on the production data of the sawmills, the average travelling distance from the rubber plantation to the sawmills was 150 km. An average of 0.30 L of diesel fuel was used to transport 1.0 m^3 of rubberwood saw logs 1 km. The assessment of the energy value for diesel fuel through the high heating value (HHV) approach yielded 10.9 MJ/m^3. As a result, the study indicated an emission of 0.82 kg CO_2-eq/m^3.

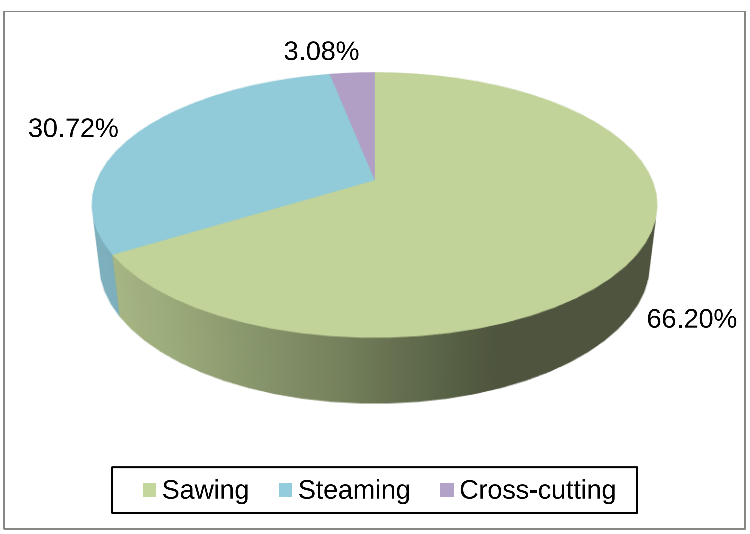

Fig. 3. The proportion of carbon footprint on the basis of sawmilling activity

Sawmill process

The rubberwood sawmilling processes was comprised of log steaming, sawing, and crosscutting (Fig. 3). In this study, the amount of carbon footprint from the sawmilling activities was 51.8 kg CO_2-eq/m^3.

Freshly cut rubberwood saw logs are susceptible to attack by wood-boring insects and fungi due to its porous structure and high chemical content (free sugars and starch) (Teoh *et al.* 2011). Although the strength properties of the wood were not affected, the non-durability of rubberwood-sawn timber caused a challenge in the value-added wood products manufacturing industry, particularly in the furniture sector. Subsequently, rubberwood-sawn timber is normally treated with chemical preservatives after the sawing process (Ratnasingam and Scholz 2009). Nevertheless, freshly cut rubberwood saw logs are usually stored in heated water ponds to minimize biodegradation and leach out the excess starch and sugar from the saw log prior to sawing. The findings from this study showed that the sawmills used electricity and woody biomass to heat up or steam the rubberwood saw logs during storage. As a result, an average of 15.9 kg CO_2-eq was calculated from the use of 6.47 kWh/m^3 electrical energy.

Sawing transformed rubberwood logs into rough green sawn timber. Electrical energy was used to operate the band saws and conveyors. Based on the observation from the sawmills used, the emission of GHGs was 66.2%. The electricity consumed to saw rubberwood logs was dependent on the volume of logs processed. Hence, a smaller volume of sawing resulted in less electricity consumption and *vice-versa*. It was clear from this study that the crosscutting of the sawn timber boards did not add a noticeable amount to the carbon footprint. From Fig. 3, it can be seen that 3.08% of the total carbon footprint was contributed by crosscutting.

Off-road transportation

In the sawmilling activity, off-road transportation had the smallest contribution to the total carbon footprint. The study enumerated that an average of 3,750 L of diesel fuel was used to carry rubberwood saw logs and sawn timber within the mills for the period of one year. Based on this data, for 1 m^3 of rubberwood rough green sawn timber, a 0.26 kg CO_2-eq carbon footprint was calculated.

Comparison with other Carbon Footprint Studies

In this study the carbon footprint of rubberwood rough green sawn timber production was established. The assessment of the carbon footprint of rubberwood rough green sawn timber from the cradle-to-gate life cycle stage was 52.9 kg CO_2-eq/m^3. The carbon footprint for other wood species from sawmilling activities was compared to the results of this study (Table 2). It appeared that rubberwood rough green sawn timber production led to a comparatively lower release of CO_2-eq. The observed differences in the carbon footprint between the sawn timbers of different wood species can be accounted by the characteristics of the saw logs, wood properties, saw mill yield, *etc.* (Ramasamy *et al.* 2015).

Martínez-Alonso and Berdasco (2015) argued that it was not conceivable to perform a comparative study of its carbon footprint with other wood species, although there might have been similarities in terms of a methodological approach. The possible noted factors were the sawmill process, inconsistency in the system boundary, sawmill efficiency, differences in emission factors, and transportation activities. In addition, another viewpoint from Ratnasingam *et al.* (2015) that needs to be considered is the log characteristics. With the findings of this study, the implausible comparison of the carbon footprint with other wood species is given noteworthy attention on account of the perspectives given by Martínez-Alonso and Berdasco (2015) and Ratnasingam *et al.* (2015).

Table 2. Carbon Footprint Assessment from Previous Studies

Species	Scientific Name	Density (kg/m^3)	Carbon Footprint (kg CO_2-eq/m^3)	References
Douglas Fir	*Pseudotsuga menziesii*	510	353	Milota *et. al.* (2005)
Western Hemlock	*Tsuga heterophylla*	429	258	Milota *et. al.* (2005)
Pine	*Pinus radiata*	550	398	McCallum *et al.* (2009)
Ash	*Fraxinus* spp.	449	407	PE International AG (2012)
Beech	*Fagus* spp.	417	377	
Hickory	*Carya* spp.	705	463	
Hard Maple	*Acer saccharum*	833	394	
Soft Maple	*Acer* spp.	737	390	
Red Oak	*Quercus rubra*	705	496	
White Oak	*Quercus alba*	545	556	
Walnut	*Juglans* spp.	769	427	
Light Red Meranti	*Shorea* spp.	747	211	Ramasamy *et al.* (2015)
Dark Red Meranti	*Shorea* spp.	768	337	Ramasamy *et al.* (2015)
Sweet Chestnut (air-dried sawn timber)	*Castanea sativa* Mill.	560	95.2	Martínez-Alonso and Berdasco (2015)
Sweet Chestnut (kiln-dried sawn timber)		560	383.7	

Sawmill process

The first aspect to consider is the sawmilling activity. Generally, the final product from sawmilling is rough green sawn timber or kiln-dried sawn timber, depending on the customers' demand (Ratnasingam *et al.* 2015; Ramasamy *et al.* 2015). Studies conducted by Kinjo *et al.* (2005), Milota *et al.* (2005), and PE International AG (2012) focused on kiln-dried sawn timber as the final product. In accordance to the study by Martínez-Alonso and Berdasco (2015), air-dried and kiln-dried sawn timber showed markedly different carbon footprints due to their variations in electrical energy consumption. Kiln-dried sawn timber production required high amounts of electrical energy for the drying activity (McCurdy *et al.* 2006). As further explained by Klitzke and Batista (2008), the quantity of sawn timber dried with different dimensions, air velocity, and types of sawn timber (planed or rough sawn timber) also had a strong influence on the amount of electrical energy consumed.

Inconsistency in system boundary

The formation of the system boundary relies on the selection of the life cycle stage. A complete life cycle stage begins with resource extraction, followed by production, use, and finally disposal, a process that is well-known as cradle-to-grave. There have been no environmental assessment studies associated to the sawmilling sector that fulfilled the complete life cycle stage. In fact, two types of life cycle stages were applied to assess the environmental profile in the sawmilling sector, namely cradle-to-gate and gate-to-gate (Kinjo *et al.* 2005; Milota *et al.* 2005; McCallum 2009; PE International AG 2012; Martínez-Alonso and Berdasco 2015; Ramasamy *et al.* 2015). The life cycle stage of gate-to-gate assessed the carbon footprint in the production line only. In contrast, cradle-to-gate begins from resource extraction and exists through the end of the production line. The difference that can be noted was the method approach in the resource extraction segment. A study done by PE International AG (2012) and Martínez-Alonso and Berdasco (2015) involved the harvesting operation. In the case of McCallum (2009), apart from the harvesting operation, the study covered management activities and road operations. However, when compared with this study, the forestry activity was quite simplified because the carbon footprint assessment focused primarily on the transportation of saw logs from the rubber plantations to the sawmills only.

Sawmill efficiency

Sawmill efficiency was related to its recovery factor. Recovery can be described as the amount and type of product that can be produced out of a given quantity of input. The milling efficiency impinges on the sawn timber recovery through features such as saw kerf use, sawing practice, and the size target and control of the final products manufactured. According to Ratnasingam *et al.* (2015), the different characteristics of hardwood logs and softwood logs influence the application of technology in the sawmill, which affected the level of efficiency. Therefore, the level of technology in sawmills is best to be determined based on the desired sawmilling efficiency. In this study, the relatively low recovery of rubberwood rough green sawn timber revealed the use of noneconomic technology for the conversion of rubberwood logs into sawn timber.

Different emission factors

One of the important aspects stressed by Martínez-Alonso and Berdasco (2015) was the use of different emission factors. The selection of emission factors is subjected to the reliable sources in agreement with the scope of the study that is performed. Some studies used the global emission factors, namely the International Panel Climate Change (IPCC). In contrast, some studies used national emission factors (Martínez-Alonso and Berdasco 2015). The use of different emission factors by Berg and Karjalainen (2003) for the calculation in forest operations also resulted in different GHGs emissions.

Transportation activities

The emissions from the transportation of saw logs to the sawmill varied in terms of fuel sources used, types of transportation, and the distance travelled (Milota *et al.* 2005). Lindholm and Berg (2005) conducted a study of on-site transportation. The study covered the fuel consumption of different types of transportation modes to carry logs from forests to industrial sites. A break-even analysis was conducted by McCallum (2009) to determine the transportation energy when logs travelled by road and were shipped to other countries. A broader perspective was adopted by PE International AG (2012). The report evaluated the distances and modes of transportation from the sawmill to the kiln facility, from the kiln facility to the port, shipping, and from the final transportation to the customer.

Log properties

Generally, Ratnasingam *et al.* (2015) highlighted that the amount of electricity consumed when cutting saw logs appeared to depend on the saw log volume processed. A large volume of logs led to more electrical energy consumption and *vice-versa* (McCurdy *et al.* 2006). Moreover, the variability of electrical energy consumption can also be explained by the difference in the density of the wood species (Table 2). The variability in the electrical energy consumption during the cutting process, particularly in the amount of electricity consumed, can be explained by the difference in the density (Klamecki 1979). Gopalakrishnan *et al.* (2012) pointed out that a large volume of logs required more energy due to a higher number of cuts required. In addition, denser wood may take longer to dry, which in turn would impose a higher energy demand. As a consequence, the release of CO_2-eq would be proportionately higher.

The Green Status of Rubberwood-sawn Timber

Table 3 reveals the comparative carbon footprint between the rubberwood and Dark Red Meranti sawn timber production within the whole sawmilling industry in Malaysia (2015 Production data). Contrary to common belief that a higher production volume often leads to higher wastage, the rubberwood in this study had a much higher carbon footprint as compared to the Dark Red Meranti (*Shorea* spp.), despite the much lower production volume of the Dark Red Meranti. This was most likely due to its substantially higher wastage in the mill and harvesting-sites.

Table 3. A Comparison of the Carbon Footprint of Rubberwood and Dark Red Meranti Sawn Timber Production in Malaysia (2015)

Descriptions	Unit	Rubberwood	Dark Red Meranti
Input of logs to sawmills	mil m^3	3.1	2.1
Sawn timber produced	m^3	780,000	1,410,000
Waste types in mill	Shavings (m^3)	-	157,182
	Sawdust (m^3)	3,944	249,918
	Splinters (m^3)	12,528	120,267
	Off-cuts (m^3)	1,670,400	162,633
Total wastage in mills	m^3	1,686,872	690,000
Wastage on harvesting site	mil m^3	3.8	0.46
Relative amount of total waste material	%	122.58	21.90
Carbon footprint			
Wastage on harvesting site	mil kg CO_2-eq	10,580,476.8	181,960.84
Transportation	mil kg CO_2-eq	0.64	2.28
Steaming	mil kg CO_2-eq	12.41	-
Sawing	mil kg CO_2-eq	27.98	169.36
Total carbon footprint	mil kg CO_2-eq	10,580,517.83	182,132.48
	mil kg CO_2-eq/m^3	13.56	0.13
* Calculation of the carbon footprint of waste was done in accordance with the guideline from IPCC (2006)			

The different wastage factors for these two wood species can be accounted for from the different stumpage values of the logs. The Dark Red Meranti logs fetched a remarkably higher value than the rubberwood logs, which should encourage loggers to extract as much wood as possible during the harvesting and sawmilling activities (Ratnasingam and Scholz 2009). The mobile band-sawing technology so widely practiced in the rubberwood saw milling sector also contributed to inefficiency, which translated to a higher carbon footprint. Furthermore, the harvesting technique used for extracting rubberwood logs, which currently focuses on woody biomass above 10 cm in diameter, must also be improved to reduce waste.

Compared to the Dark Red Meranti sawn timber from the natural forest, it was apparent that the position of rubberwood as a green material appears to be weak and questionable from the perspective of its higher carbon footprint. Therefore, to improve the green label of the material, it is important that the rubberwood sawmilling industry strives towards improving the recovery of material both at the harvesting and mill site through the use of appropriate technology.

CONCLUSIONS

1. This study provided valuable information on the carbon footprint of rubberwood rough green sawn timber production in Peninsular Malaysia using the cradle-to-gate life cycle stage.
2. The carbon footprint was identified as 52.9 kg CO_2-eq for 1 m^3 of rubberwood rough green sawn timber. The electrical energy consumption during the sawing process contributed the most in GHGs emission.
3. When compared to the Dark Red Meranti sawn timber, the production of rubberwood-sawn timber had a much higher carbon footprint due to the high wastage on the harvesting site and within the sawmill.
4. To improve the green label of rubberwood, it is important to ensure that more efficient harvesting and sawing technologies are used to minimize waste.

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