Assessment of Environmental Emissions from Sawmilling Activity in Malaysia

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The sawmilling sector is the backbone of the Malaysian wood-based industry. Sawn timber is used extensively for further manufacturing of secondary wood-based products. The conversion of saw-logs into sawn timber releases several gases into the atmosphere, and these may contribute to environmental burdens as well as environmental impacts. Thus, this study aims to determine the environmental performance from gate-to-gate in the sawmilling industry using the life cycle assessment technique. Data pertaining to the saw-logs and energy consumption was calculated, and the environmental performance was assessed. The study focused on two different size sawmills and two tropical hardwood species. The findings concluded that several types of gases namely, CO_2, CH_4, NO_x, N_2O, SO_2, and CO were discharged to the environment as a result of sawmilling processes. The discharge of these gases impacted the environment in the form of global warming, acidification, human toxicity, eutrophication, and photo-oxidant formation potentials.

Keywords: Environmental burdens; Environmental impacts; Life cycle; Sawmilling; Meranti

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INTRODUCTION

The Malaysian wood-based industry began in the early 1900s. While it was primarily focused on meeting the domestic demand at the time, it has been transformed into a large, export-oriented industry, producing a wide variety of value-added products (National Timber Policy 2009). The industry has gained a prominent socio-economic status by contributing more than RM 20 billion in annual export earnings and providing employment to almost 226,000 workers over the last few years (MTIB 2012). In 2011, a total of 3975 manufacturing entities were operating in the Malaysian wood-based industry (Table 1).

The wood-based industry has emerged as one of the most important, prominent, and fastest growing manufacturing sectors in the Malaysian economy. Despite the growing importance of value-added wood product manufacturing, the sawmilling sector remains the backbone of the wood-based industry (Baharuddin 1984; National Timber Policy 2009). Sawmilling produces sawn timber and wood waste that are exploited by the other wood-based industries to be further processed into value-added products, such as furniture, wood-based panels, moulding, joinery, *etc*. Since the implementation of the 1st Industrial Master Plan (IMP) in 1986 by the Malaysian government, the sawmilling industry has been accorded lesser importance (Menon 2000).

Table 1. Number of Wood-Based Industries in Malaysia

Mills	Number of mills
Furniture and wood workings	2291
Sawmilling	1006
Mouldings	338
Plywood/veneer/blockboard	230
Kiln drying	190
Wood preservation	98
Chipboard/particleboard	46
Laminated board	44
Builders, joinery, and carpentry	29
Others	3
Source: Malaysian Timber Industry Board (2012) Note: Others comprise of pulp and paper (1), matches (1), and pencils (1)	

With a reduced supply of saw-logs from natural forest in the country, which practices Sustainable Forest Management (SFM), the capacity for utilization of wood within the sawmilling industry in Malaysia has also suffered (Table 2).

Table 2. The Capacity Utilization of Sawmilling in Malaysia

Year	Capacity utilization (m^3)	Capacity utilization (%)
2003	12,271	23.9
2004	10,899	29.4
2005	10,953	29.5
2006	11,016	27.4
2007	11,096	24.0
2008	11,137	21.4
2009	11,182	18.6
2010	11,276	23.6
2011	11,411	23.4
Source: Ministry of Plantations Industries and Commodities (2012)		

Furthermore, the technology used in the Malaysian sawmilling sector is old and obsolete (Ong 1986; Ho and Gan 2003). In general, sawmills fail to modernize and automate because of a lack of finances. It has been noted that the different characteristics of the tropical hardwood and softwood saw-logs, together with the variable market demands for these sawn timbers, makes the application of new technology in the Malaysian sawmilling sector uneconomical (Yap 2004).

As a result, the Malaysian sawmilling sector suffers from low productivity and generates a large volume of waste. According to the ITTO-CITES Project report (2010), the generation of wood waste in the sawmilling sector of Peninsular Malaysia was approximately 45 to 50% of the total volume of saw-log input. On the other hand, the sawmilling sector is also energy-intensive. As reported by Mahlia (2002), the electrical energy consumed during the sawmilling processes is generated off-site at power stations that burn fossil fuels. During the sawmilling process, a substantial amount of thermal energy is also produced on-site. The combustion of fossil fuels for energy generation discharges gases, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), mono-nitrogen oxides (NOx)—which include nitric oxide (NO) and nitrogen dioxide (NO_2), carbon monoxide (CO), sulphur dioxide (SO_2), non-methane volatile organic compounds (NMVOC), and particulates to the environment (Mahlia 2002; Ong *et al.* 2011; Rosnazri *et al.* 2012). These gases have a negative impact on the environmental air quality.

A number of studies have investigated the effects of resource consumption in sawmilling and the resultant environmental profiles. These studies have revealed that the consumption of resources results in the discharge of a variety of gases in different quantities into the environment (Kinjo *et al.* 2005; Eshun *et al.* 2010; Puettmann *et al.* 2010; Bergman and Bowe 2012; Tellnes *et al.* 2012). Eshun *et al.* (2010) highlighted that the environmental emissions are different between countries and sawmills as a result of the different technologies, methods, and environmental standards applied. It is widely believed that the effects of sawing softwoods is less environmentally damaging compared to hardwoods, although no conclusive reports are available at this time (Bergman and Bowe 2012). In addition, the emission of several gases subsequently impacts the environment in the form of global warming, acidification, human toxicity, ozone depletion, photo-oxidant formation, material depletion, energy depletion, and eutrophication potentials (Kinjo *et al.* 2005; Puettmann *et al.* 2010; Eshun *et al.* 2011; PE International AG 2012; Tellness *et al.* 2012). Consequently, the issue of environmental performance from the sawmilling industry has become a topic of intense debate both at the national and international levels (Eshun *et al.* 2010).

Although alternative materials, such as steel, plastic, and concrete, can replace wood for many applications, this practice is not desirable, as these materials have been reported to contribute to greater environmental burdens compared to wood (González-Garcia *et al.* 2012). In view of this difference, research on the environmental performance of the sawmilling sector is of high interest, especially in Malaysia, which has a large wood-based industry. Therefore, a study of the environmental performance of the sawmilling sector in Peninsular Malaysia using the life cycle assessment (LCA) technique was carried out. This study will help to fill the existing knowledge-gap in the environmental performance assessment of the sawmilling sector in Peninsular Malaysia. The results from this study will provide benchmark values for the environmental profiles contributed by the sawmilling industries in the country, which will help formulate the necessary strategies for the overall improvement of the industry.

EXPERIMENTAL

The LCA analytical tool was used in this study to evaluate the environmental performance as a result of the resources consumption during the production of rough green sawn timber. The assessment of the burdens and potential environmental impacts was determined on the basis of LCA methodological framework, which consists of four phases that are the goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and life cycle interpretation. The methodological framework was evaluated in accordance to the revised ISO 14040 (2006) Standards for Framework and Guidance and the ISO 14044 (2006) Standards for Technical Requirements and Guidelines.

Goal and Scope Definition Phase

The goal and scope definition phase framed the LCA study, and the methodological choices were clearly defined. The methodological framework was developed corresponding to the study scope, establishment of system boundaries, description of functional units, and the selection of the allocation approach.

Scope of the study

The study assessed the environmental performances from the sawmilling sector. Two sawmills were chosen for this study. The selection of sawmills in this environmental burdens assessment was presumed to be representative of the overall sawmilling sector that produces rough green sawn timber of *Meranti* species in Peninsular Malaysia. In addition, the technology applied in the sawmilling sector in Peninsular Malaysia was comparable (Ho and Gan 2003). Hence, the findings of the environmental performances in this investigation provided benchmark values for the sawmilling sector, which is considered the oldest wood-processing industry in the country.

The first sawmill, referred to as sawmill A, is the biggest sawmill in Peninsular Malaysia. Sawmill A was set as the base scenario for this study. Meanwhile, the second sawmilling, referred to as sawmill B, is a medium-sized sawmill. The purpose to include medium-sized sawmill in this study was to determine any notable differences from the resources consumption to the environmental performance when compared to sawmill A. Small-size sawmills do exist, but mills of this type provide custom wood products only. In addition, smaller mills tended not to keep accurate production records, and even some of the large hardwood sawmills did not have primary mill data requested. The combination of sawmill A and sawmill B produced 25% to 30% of sawn timber out of the total output in Peninsular Malaysia. Table 3 summarizes the differences between the two sawmills.

Table 3. Differences Between Sawmill A and Sawmill B

Descriptions	Sawmill A	Sawmill B
Establishment	1978	1981
Capacity (m^3/month)	3500	2800
Workforce	240	150

Meanwhile, sawmills A and B were similar in terms of the sawing operational parameters. Saw blade properties for the head saw, re-saw, and cross-cut saw are as specified in Table 4. This is also fixed for both Light Red *Meranti* and Dark Red *Meranti* wood species. In view of the fact that the sawing operational parameters and saw blade properties were similar for both sawmills, as well as wood species, these were treated as the constant factors.

Table 4. The Fixed Factors of Sawing Operational Parameters and Saw Blade Properties

Fixed factors	Descriptions	Band saw	Circular saw
Sawing Operational Parameters	Feed speed (m/min)	2.1	1
	Saw kerf (mm)	1.5	6
	Depth of cut (inches)	0.28	0.15
Saw blade properties	Bite per tooth	14	20
	Gullet capacity (inches)	3	1.5
	Length (m)	-	2.3
	Diameter (mm)	-	550
	Pitch (inches)	2.1	1

Description of the sawmills under study

The assessment of environmental performance associated with the production of rough green sawn timber in both sawmills used the gate-to-gate approach, which assessed the saw-logs as they entered the mill for cutting up until the production of rough green sawn timber. The primary breakdown process cut the saw-logs into flitches. These flitches were then moved along the conveyor to be re-sawn into sawn timber in the secondary breakdown process. The quality control process ascertained that all defects spotted on the sawn timber were cross-cut and removed. The rough green sawn timbers were then ready for shipment. Off-road transportation activities, including the transportation of the saw-logs and sawn timbers within the sawmills, were included in this research assessment.

Several types of hardwood saw-log species were used in sawmill A and sawmill B for rough green sawn timber production. In this study, however, the assessment of environmental performances focused primarily on the *Meranti* species. According to Blaser *et al*. (2011), the *Meranti* species is largely exploited for sawn timber production in Peninsular Malaysia. Furthermore, *Meranti* sawn timber is well established in the local and international markets. Therefore, this study focused on the Light Red *Meranti* and Dark Red *Meranti* saw-logs in view to the fact that the sawmills chosen for this study had a consistent supply of these species year-around.

Meanwhile, the analysis of energy consumption was identified to be electrical energy and diesel fuel energy. Electrical energy was used to operate the primary breakdown, secondary breakdown, quality control, and conveyor belts for the conversion of saw-logs into sawn timber, while diesel fuel energy was used for off-road transportation activities.

System boundary

The system boundary was set up to display the flow of the inputs, outputs, and the environmental releases during the rough green sawn timber production within the gate-to-gate production. The inclusion and exclusion of certain aspects in the setting up of the system boundary is presented in Table 5.

Table 5. The Inclusions and Exclusions in System Boundary

Included	Description
Manufacturing process	- The flow of logs - The consumption of electricity - Production of final product, co-products, and environmental emissions
Off-road transportation	- The consumption of diesel fuel in front-end loaders
Excluded	Description
Machinery	- The contribution of heat and noise from machines and equipment in sawmilling
Human labour	- Energy from human labour - Transportation used by the labours to come to the plants

The formation of the system boundary, which was reflected in the inclusion and exclusion of the aspects shown in Table 5, consisted of the foreground (on-site) and background (cumulative) system boundaries, as shown in Fig. 1. Within the solid line contains the background system boundary, while the foreground system boundary is shown within the dotted line. The foreground system boundary evaluated the emissions that occurred in the sawmills from a set of unit processes (on-site emission). Meanwhile, the background system boundary included the emissions from the consumption of materials and electrical energy.

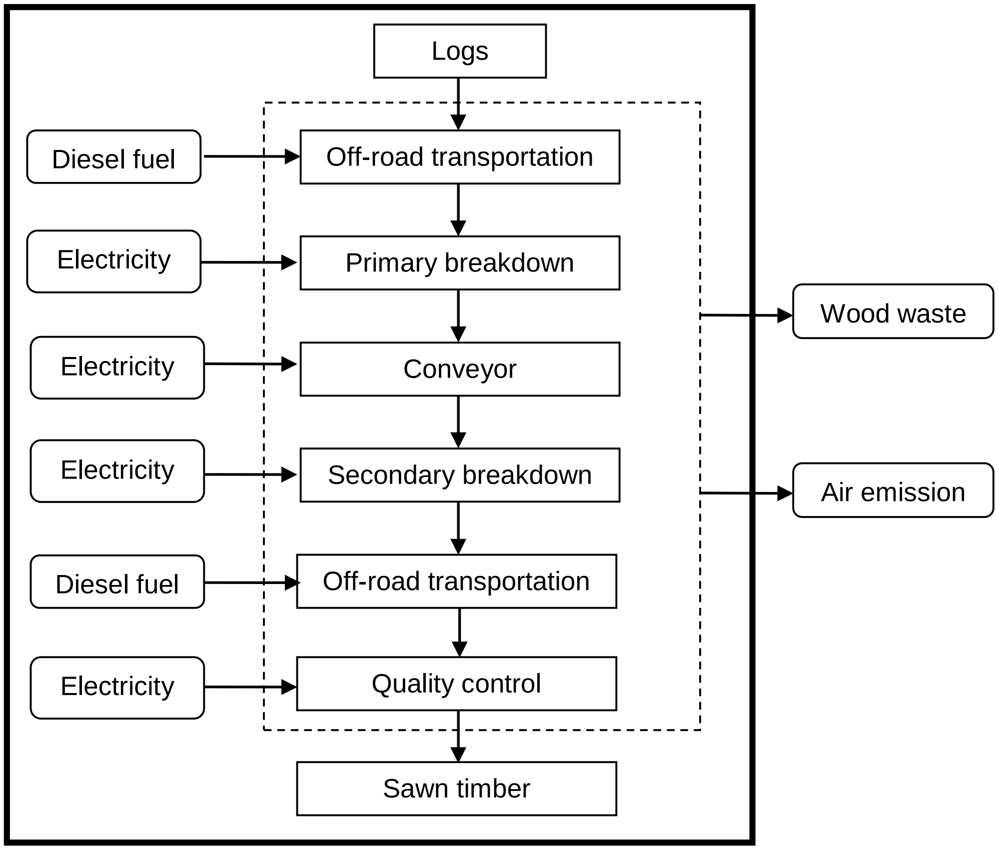

Fig. 1. System boundaries of sawn timber production

Functional unit

The investigated woods were Light Red *Meranti* and Dark Red *Meranti* rough green sawn timber. By definition, the functional unit describes the quantitative description of an investigated product (Finnveden *et al.* 2009). In this study, volume was used as the functional unit for the outputs. The functional unit used in this study for the environmental emission assessment was therefore standardized, on a as per-unit volume basis for 1.0 m^3 of Light Red *Meranti* and Dark Red *Meranti* rough green sawn timber.

Life Cycle Inventory (LCI)

The inputs used during the manufacturing process of rough green sawn timber were saw-logs and energy. The inputs data were collected representing one full calendar year in 2013. The inventory method quantified the inputs used in the sawmilling activities. The outputs consisted of products, wood residues, and environmental emission, which were then evaluated based on the resources consumed.

Data collection and data analysis of material flow

The first part of the data collection was to determine the flow of the saw-logs. The recovery approach was used to evaluate the yield of rough green sawn timber. The study applied the cubic recovery percent method in order to determine the yield of sawn timber. The calculation of sawn timber recovery (%) is shown in Eq. 1.

$$Sawn\ timber\ recovery\ (\%)\ =\ \frac{total\ volume\ recovered\ (m^3)}{volume\ of\ \log input\ (m^3)} \times 100 \quad (1)$$

Once the flow of saw-logs was determined, the allocation approach was selected. The flow of saw-logs in the unit production processes not only produced rough green sawn timber, but it also produced wood residues in the form of off-cuts, shavings, sawdust, and splinters. These wood residues were not used by the sawmills. Instead, they were sold to other mills. Therefore, in this study, the physical relationship allocation was chosen, and sawn timber was regarded as the main and only product, while other products were regarded as waste for sawmill A and sawmill B.

Data collection and data analysis of energy consumption

Meanwhile, the analysis of energy consumption was categorized into the electrical energy and diesel fuel energy. The calculation of electrical energy consumption was based on Eq. 2 (Devaru *et al.* 2014), in which the data was collected using an electricity meter (Crystal Instrumentation P-04, Taiwan).

$$Energy\ consumption\ (kWh) = \frac{\sqrt{3} \times V \times I \times cosine\ (\emptyset) \times number\ of\ hours}{1000} \quad (2)$$

In Eq. 2, V is the average voltage (V), I is the average amperage (A), and cosine (Φ) is the power factor.

The electrical energy consumption (kWh) of the conveyor belt was estimated on the basis of the load factor, motor efficiency, and the operating hours of the motors, using Eq. 3 (Devaru *et al.* 2014).

$$Energy\ consumption\ (kWh) = \frac{horsepower \times 0.746\ kW \times load\ factor \times operating\ hours}{motor\ efficiency} \quad (3)$$

The input of diesel fuel was converted into an energy value using the high heating value (HHV) concept. Equation 4 shows the calculation of the energy value for the diesel fuel.

$$Energy\ value\ (MJ)\ =\ Dieselfuel\ x\ diesel\ fuel\ density\ \times HHV \quad (4)$$

Data collection and data analysis of environmental burdens

The release of CO_2, CH_4, N_2O, NO_X, CO, and SO_2 components into the environment was calculated after the resource consumption was determined. The calculation for every component was done based on the activity data and emission factors, as shown in Eq. 5 (International Panel of Climate Change 2006). Activity data were associated with the measurement of electrical energy and diesel fuel energy during the sawn timber production. The emission factor was the representative value given for CO_2, CH_4, N_2O, NO_X, CO, and SO_2 that was related to the activity.

$$Environmental\ emission\ (kg) = Activity\ data \times emission\ factor \quad (5)$$

Life Cycle Impact Assessment

The study continued to assess the potential environmental impacts once the elements discharged to the environment were identified. The assessment of potential environmental impacts associated to the production of Light Red *Meranti* and Dark Red *Meranti* rough green sawn timber in sawmill A and sawmill B was performed by means of the centre of Environmental Science, Leiden University (CML) baseline method. The selection of the CML method was due to the fact that this approach is widely used, internationally accepted, and well recognized in the life cycle study of timber products (Eshun *et al.* 2011). The CML methodology was accounted for based on the "Operational Guide to Life Cycle Assessment" (Guinée *et al.* 2001). The LCIA study was carried out on the basis of classification and characterization phases, as Rivela *et al.* (2007) mentioned that it is the least subjective approach.

Five potential environmental impacts categories were selected in this study, comprising of global warming, acidification, human toxicity, eutrophication, and photo-oxidant formation potentials. In the classification phase, the elements discharged to the environment, which are the CO_2, CH_4, N_2O, NO_X, CO, and SO_2, were assigned into the potential environmental impacts categories as shown in Table 6.

Table 6. Classification of Substances into the Categories of Potential Environmental Impacts

Impact categories	Substances
Global warming potentials	CO_2, CH_4 and N_2O
Acidification potentials	SO_2 and N_2O
Eutrophication potentials	CO NO_2, SO and CH_4
Photo-oxidant formation potentials	NO and NO_2
Human toxicity potentials	SO_2 and NO_2

Once the substances were assigned into the potential environmental impacts categories, the characterization step translated the related substances into the potential environmental impacts by using the equivalency factors. The calculation used was based on Guinee *et al.* (2001), as shown in Eq. 6,

$$Potential\ environmental\ impacts = EF \times M\ (kg) \tag{6}$$

where EF is the equivalency factor, while M represents the mass of the substance. The details of the equivalency factors for global warming, acidification, human toxicity, eutrophication, and photo-oxidant formation potentials are shown in Table 7.

Table 7. Equivalency Factors for Potential Environmental Impacts

Impact Category	Substances	Equivalency factor	Description of equivalency factor
Global warming potentials	CO_2 CH_4 N_2O	1 kg = 1 CO_2 -eq 1 kg = 25 CO_2-eq 1 kg = 298 CO_2-eq	Translated into kg CO_2-eq
Acidification potentials	SO_2 NOx	1 kg = 1.2 SO_2-eq 1 kg = 0.5 SO_2-eq	Translated into kg SO_2-eq
Eutrophication potentials	NOx N_2O	1 kg = 0.13 PO_4^{3-}-eq 1 kg = 0.13 PO_4^{3-}-eq	Translated into kg PO_4^{3-}-eq
Human toxicity potentials	SO_2 NO_2	1 kg = 0.096 1,4-DCB-eq 1 kg = 1.2 1,4-DCB-eq	Translated into kg 1,4-DCB-eq
Photo-oxidant formation potentials	CO NO_2 SO_2 CH_4	1 kg = 0.027 C_2H_4-eq 1 kg = 0.028 C_2H_4-eq 1 kg = 0.048 C_2H_4-eq 1 kg = 0.006 C_2H_4-eq	Translated into kg C_2H_4-eq

Life Cycle Interpretation

The findings were explained through the life cycle interpretation in accordance with the study goal. In this study, the interpretation phase highlighted the effect of sawmilling and wood species factors on the environmental burdens. Further, this stage of LCA interpreted and discussed the potential environmental impacts from both sawmills and wood species. The results were statistically analyzed using the Statistical Package for the Social Science 20.0 (SPSS; IBM, USA).

RESULTS AND DISCUSSION

The findings from the LCI study focused on the Light Red *Meranti* and Dark Red *Meranti* rough green sawn timber production in sawmill A and sawmill B are presented in this section. All of the findings were analyzed on the basis of mean values per m^3 of Light Red *Meranti* and Dark Red *Meranti* rough green sawn timber. The results of this study are presented in four parts: (1) product yield; (2) energy consumption of electricity and diesel fuel; (3) environmental burdens; and (4) potential environmental impacts.

Product Yield

The flow of saw-logs in the manufacturing process produced rough green sawn timber as the main product. The yield of Light Red *Meranti* and Dark Red *Meranti* rough green sawn timber was enumerated by applying the cubic recovery technique. The method of cubic recovery was selected for this study based on the report by Lin *et al.* (2011), who suggested that the cubic recovery method is more practical and more accurate than the lumber recovery factor (LRF).

Figure 2 shows the mean recovery of Light Red *Meranti* and Dark Red *Meranti* rough green sawn timber determined from sawmill A and sawmill B.

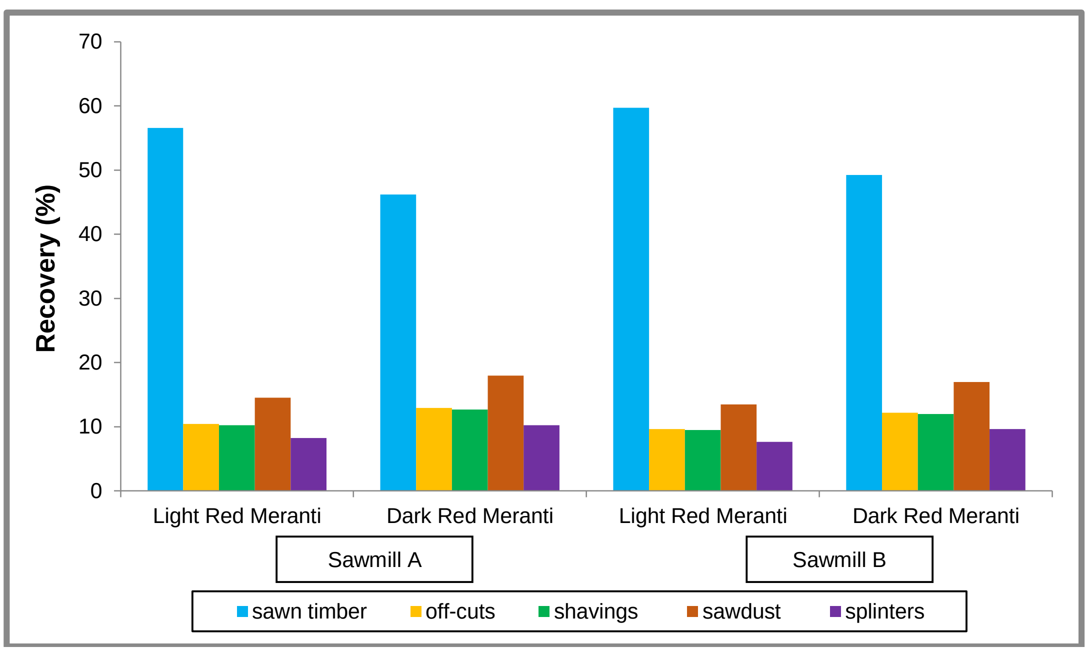

Fig. 2. The average recovery of sawn timber and co-products in sawmill A and sawmill B

The mean recovery of Light Red *Meranti* and Dark Red *Meranti* rough green sawn timber in sawmill A differed by 10.36%. Likewise, the mean of the sawn timber recovery for Light Red *Meranti* was 10.49% higher than Dark Red *Meranti* in sawmill B. On the other hand, in a comparison between sawmills, sawn timber recovery for both species in sawmill B yielded greater quantities than sawmill A by 3.23% and 3.05% for Light Red *Meranti* and Dark Red *Meranti*, respectively.

Apart from the production of rough green sawn timber, the flow of saw-logs also resulted in wood losses in the form of off-cuts, sawdust, shavings, and splinters. These wood losses were not further used in sawmill A and sawmill B. Off-cuts, sawdust, shavings, and splinters were eventually sold to other mills in which off-cuts were recovered for other wood products, while sawdust, shavings and splinters were used for energy generation in the boilers. As shown in Fig. 2, the proportion of off-cuts, sawdust, shavings, and splinters was slightly higher for the Dark Red *Meranti* in both sawmills. When comparing of Dark Red *Meranti* between sawmills A and B, a higher proportion of volume was observed in sawmill A, with a small difference of 0.73%, 0.72%, 1.02%, and 0.58% for off-cuts, sawdust, shavings, and splinters, respectively.

Energy Consumption

The sources of energy used in the sawmilling activities were identified as electrical energy and diesel fuel energy.

Electrical energy consumption

Electricity was used in sawmills A and B to run the motors for the sub-system unit processes comprising the primary breakdown, secondary breakdown, quality control, and conveyor belt. Energy used to operate the sub-system processes was defined as process energy (Vigon *et al.* 1993). Figure 3 shows the mean of the electrical energy used by sawmill A and sawmill B to cut 1 m^3 of Light Red *Meranti* and Dark Red *Meranti* rough green sawn timber.

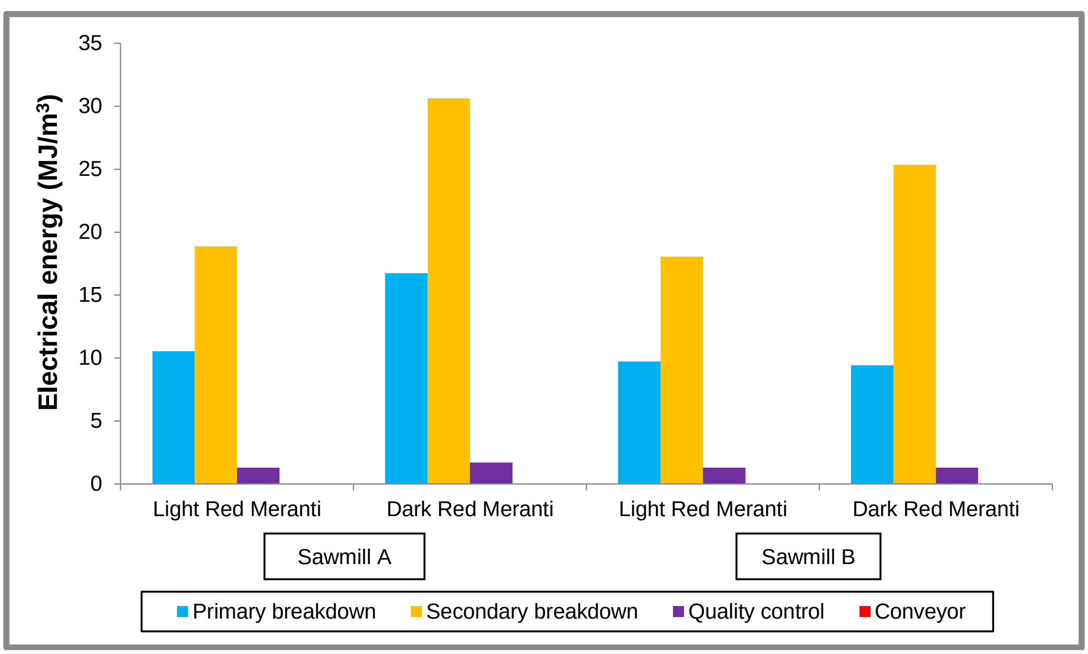

Fig. 3. The average of electrical energy consumption in sawmill A and sawmill B

Overall, the average electrical energy consumed in sawmill A was 30.70 MJ/m^3 and 49.10 MJ/m^3 for Light Red *Meranti* and Dark Red *Meranti*, respectively. Based on Fig. 3, the difference in electrical energy consumption between the Light Red *Meranti* and Dark Red *Meranti* in the primary breakdown, secondary breakdown, quality control, and conveyor belt sub-systems was observed to be 6.19 MJ/m^3, 11.77 MJ/m^3, 0.44 MJ/m^3, and 0.006 MJ/m^3, respectively. In sawmill B, the mean electrical energy consumed for Light Red *Meranti* and Dark Red *Meranti* was 29.08 MJ/m^3 and 36.08 MJ/m^3, respectively. Similar to sawmill A, the electricity used to operate the sub-system processes during the sawmilling activities was higher when cutting Dark Red *Meranti*. These differences were 0.31 MJ/m^3, 7.31 MJ/m^3, 0.004 MJ/m^3, and 0.005 MJ/m^3 in the primary breakdown, secondary breakdown, quality control, and conveyor belt sub-systems.

Diesel fuel energy consumption

Diesel fuel was used in sawmills A and B for off-road transportation activities. These activities involved the carrying of saw-logs and sawn timber boards within the mills themselves. Since this study was focused on the off-site transportation activity, the fuel used was the only aspect taken into consideration. The average input of diesel fuel to move the Light Red *Meranti* and Dark Red *Meranti* saw-logs and rough green sawn timber is shown in Fig. 4. The average consumption of diesel fuel for sawmill A was evaluated at 0.24 L/m^3 and 0.38 L/m^3 for Light Red *Meranti* and Dark Red *Meranti* sawn timber, respectively. Meanwhile, the average consumption of diesel fuel for sawmill B was evaluated at 0.22 L/m^3 and 0.34 L/m^3 for Light Red *Meranti* and Dark Red *Meranti* sawn timber, respectively.

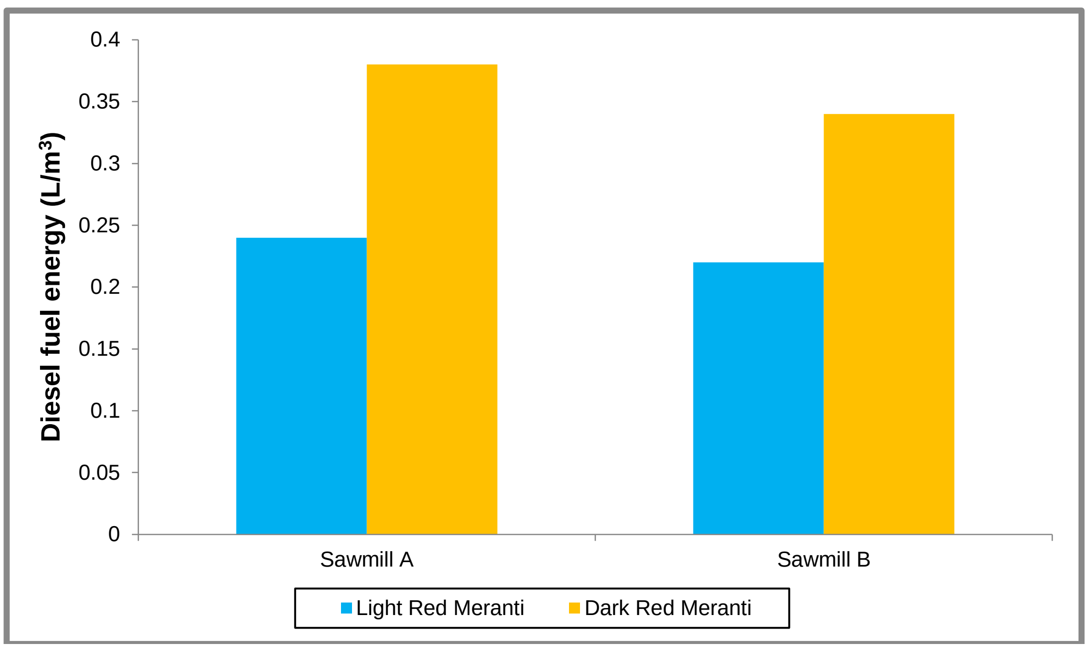

Fig. 4. The average of diesel fuel energy consumption in sawmills A and B

In addition, the energy value of diesel fuel was determined. The approach used to convert the volume of diesel fuel into the energy value was the high heating value (HHV) method. Table 8 presents the mean diesel fuel energy value for the Light Red *Meranti* and Dark Red *Meranti* for sawmills A and B, respectively.

Table 8. Average of Energy Value of Diesel Fuel

Wood Species	Sawmill A (MJ/m^3)	Sawmill B (MJ/m^3)
Light Red *Meranti*	8.96	8.26
Dark Red *Meranti*	14.18	12.74

Environmental Burdens

The use of resources in sawmilling activities consequently discharges the wood residues, CO_2, CH_4, N_2O, NOx, CO, and SO_2 in different types and quantities into the environment. The environmental emissions considered in this study were those that led to environmental burdens.

Environmental burdens associated with saw-logs consumption

As mention earlier, the conversion of saw-logs not only produced rough green sawn timber, but also resulted in wood losses in the form of off-cuts, sawdust, shavings, and splinters. However, these wood residues were not considered as environmental burden, as they were not disposed of at the landfill. In fact, these wood residues were sold to other mills for energy generation and were recovered in other mills. Emissions to the environment were only considered when a by-product remained unused for another purpose (Ingerson 2011).

Environmental burdens associated with energy consumption

The off-site electricity was generated from the burning of fossil fuels in conventional power stations. Meanwhile, diesel fuel was combusted on-site, especially for transportation activities. Saidur *et al.* (2007) described that fuel is comprised of carbon, sulfur, nitrogen, or their compounds. Inevitably, these components were emitted into the environment in different amounts, depending on the quantities and types of fossil fuel used (Puettmann *et al*. 2010). The release of these gases as a result of fuel consumption is categorized as anthropogenic emission. Anthropogenic emissions consequently are related to environmental burdens (Milota *et al.* 2005; Kinjo *et al*. 2005; Bergman and Bowe 2012).

It was noticeable from this investigation that the consumption of electrical and diesel fuel energy during the production process discharged several gases, namely CO_2, CH_4, NO_x, N_2O, SO_2, and CO. The observations in Tables 9 and 10 show that there were varied discharges of CO_2, CH_4, NO_x, N_2O, SO_2, and CO, as a result of electrical energy and diesel fuel consumption, on the basis of the wood species and the sawmill used. The release of SO_2 from diesel fuel could not be evaluated because of a lack of data. Overall, the average emission of CO_2 was the largest.

Table 9. Environmental Burdens Associated with the Energy Consumption in Sawmill A

	Light Red *Meranti*		Dark Red *Meranti*	
	Electrical energy	Diesel fuel energy	Electrical energy	Diesel fuel energy
CO_2	1.44E+00	6.64E-01	2.30E+00	1.05E+00
CH_4	7.83E-05	8.96E-05	1.25E-04	1.42E-04
N_2O	1.11E-05	5.38E-06	1.78E-05	8.51E-06
NOx	1.29E-02	9.85E-03	2.07E-02	1.56E-02
CO	2.33E-03	3.31E-03	2.96E-03	5.25E-03
SO_2	2.83E-02	-	4.53E-02	-

Similar finding have been reported in other studies such as Kinjo *et al.* (2005), Milota *et al.* (2005), Puettmann *et al.* (2010), and Bergman and Bowe (2012). It was then followed by SO_2, NO_x, and CO. Furthermore, the differences in the emission between CO_2 compared to SO_2, NO_x, and CO were noteworthy. On the contrary, the release of CH_4 and N_2O into the environment was considered minimal.

Table 10. Environmental Burdens Associated with the Energy Consumption in Sawmill B

	Light Red *Meranti*		Dark Red *Meranti*	
	Electrical energy	Diesel fuel energy	Electrical energy	Diesel fuel energy
CO_2	4.02E+00	6.12E-01	4.99E+00	9.44E+01
CH_4	7.42E-05	8.26E-05	9.20E-05	1.27E-04
N_2O	1.05E-05	4.95E-06	1.31E-05	7.64E-06
NOx	1.22E-02	9.08E-03	1.52E-02	1.40E-02
CO	2.21E-03	3.05E-03	2.74E-03	4.71E-03
SO_2	2.68E-02	-	3.33E-02	-

Effect of the Test Factors on the Environmental Burdens

The sawmills and wood species were classified as the categorical variables in this study. The effect of these categorical variables were analysed on the environmental burdens. The purpose was to carry out the analysis in order to identify any significant contribution that was made to the environmental burdens of CO_2, CH_4, NO_x, N_2O, SO_2, and CO on the basis of the two sawmills of different sizes (sawmill A and sawmill B) and two types of wood species (Light Red *Meranti* and Dark Red *Meranti*). The normality test showed that the variables of CO_2, CH_4, NO_x, N_2O, and CO were observed to be normally distributed, except for SO_2.

Statistical test for normal distribution variables

A multivariate analysis of variance (MANOVA) statistical test was applied for the normally distributed variables. The first part of the MANOVA test was to analyze the overall significance of the main effects of sawmilling and wood species, respectively, and also the interaction of sawmill and species. The overall multivariate test on the environmental burdens is shown in Table 11. The analysis shows that the main effect of the sawmill factor and the interaction of sawmill and wood species were evaluated to be non-significant, as the p-value was larger than 0.05. In the meantime, the wood species factor was the only variable with a significant effect on the environmental burden, since the *p*-value was less than 0.05. The possible reason that the sawmill factor had no effect on the environmental burdens was due to the similarity in the sawmilling conditions in terms of saw blade properties and sawing operational parameters in both sawmills. The interaction of sawmill and wood species factors was not significant and therefore the sawmill factor had little influence on the environmental burdens due to wood species.

Table 11. Multivariate Test of Variables on the Environmental Burdens

	Wilks' Lambda value	F	Hypothesis df	Error df	*p*-value
Sawmill	0.959	0.573	2	27	0.571
Species	0.781	3.796	2	27	0.035*
Sawmill*species	0.966	0.476	2	27	0.626
*Significance accepted at the 0.05 level					

The null hypothesis of no difference in environmental burden between the Light Red *Meranti* and Dark Red *Meranti* was rejected. Hence, the analysis was continued to examine the main effects of wood species on the environmental burdens. The second part of the MANOVA statistical test was identical to the five separate factorial ANOVA test if MANOVA was not opted. Leech *et al.* (2005) pointed out that an experimental-wise alpha rate of 0.05 is required in the second part of the MANOVA statistical test. The main reason was that the p-values in the multivariate test did not take into consideration that the multiple ANOVAs have been carried out. Hence, the p-value of 0.05 was divided into five, according to the total of the dependent variables (CO_2, CH_4, NO_x, N_2O, and CO), to get an adjustable confidence level. As shown in Table 12, the mean values for CO_2, CH_4, N_2O, NO_x and CO, emissions in Dark Red *Meranti* were slightly greater than those for the Light Red *Meranti*.

Table 12. Mean Comparison of Environmental Burdens between Wood Species

	CO_2	CH_4	N_2O	CO	NOx
Light Red *Meranti*	4.770	1.62E-4	1.59E-5	0.005	0.022
Dark Red *Meranti*	6.885	2.43E-4	2.35E-5	0.008	0.033

The effect of Light Red *Meranti* and Dark Red *Meranti* in the discharge of CO_2, CH_4, NO_x, N_2O, and CO was considered to be statistically significant if the p-value was less than 0.01. Nevertheless, the analysis showed no significant differences in the emission between the Light Red *Meranti* and Dark Red *Meranti*, as the *p*-value was greater than 0.01 (Table 13). The two wood species differed in terms of sawn timber dimension produced, saw logs characteristics and physical properties.

Perhaps, the variation in energy consumption was not strong enough to provide a significant difference in the environmental emission. Therefore, it can be noted that the difference in the mean release of CO_2, CH_4, N_2O, NOx, and CO was not influenced by the wood species.

Table 13. Effect of Wood Species on the Environmental Burdens

	CO_2	CH_4	N_2O	CO	NOx
Sum of squares	7.299	5.23E-08	4.51E-10	6.10E-05	0.001
df	1	1	1	1	1
Mean square	7.299	5.23E-08	4.51E-10	6.10E-05	0.001
F	4.135	5.164	7.790	6.623	5.903
p-value	0.031	0.018	0.031	0.016	0.023
*Significance was accepted at 0.01					

Statistical test for normal distribution variables

A non-parametric test (Mann-Whitney U test) was applied to determine the effect of the categorical factors on the SO_2 emission. The Mann-Whitney U test was used because the normality of SO_2 was violated. Table 14 depicts the results of the Mann-Whitney U analysis.

The findings of the statistical analysis showed that the variables, sawmill and wood species, respectively, were not statistically significant in the discharge of SO_2 emissions, since the *p*-value was greater than 0.05.

Table 14. Effect of the Sawmill and Wood Species on the SO_2 Environmental Burden

Test Factors		Mean rank	Mann-Whitney U	*p*-value
Sawmill	Sawmill A	17.81	107.000	0.445
	Sawmill B	15.19		
Wood species	Light Red *Meranti*	13.62	82.000	0.083
	Dark Red *Meranti*	19.38		

A Comparison of the Environmental Emissions in Wood Species

Generally, the release of CO_2, CH_4, NO_x, N_2O, CO, and SO_2 from Dark Red *Meranti* was greater than that of Light Red *Meranti*. As a matter of fact, the result showed that wood species factor did not affect the emission of CO_2, CH_4, NO_x, N_2O, CO, and SO_2, as the finding was non-significant between the wood species. Although the two variables did not show any differences in emissions between the Light Red *Meranti* and Dark Red *Meranti*, the overall factors that influenced these variations in emissions were highlighted.

The saw-log's density, length, diameter, volume, moisture content as well as the dimensions of sawn timber produced, for both wood species, were different. The observations in this study with regards to the variability in the energy consumption, particularly electricity, for Light Red *Meranti* and Dark Red *Meranti* saw-logs was likely caused by the differences in saw-log characteristics and physical properties. Increasing the saw-log's length and diameter would require additional energy during the cutting processes. Furthermore, cutting smaller dimension sawn timber would increase the energy demand (McCurdy *et al.* 2006).

Saw-logs of higher density require more energy and more material for a given cutting volume (Darmawan *et al.* 2008; Ratnasingam *et al.* 2008; Ratnasingam *et al.* 2009; Ramasamy and Ratnasingam 2010). In the meantime, the sawing volume of Dark Red *Meranti* in both sawmills was higher than the Light Red *Meranti*, which explains the higher use of diesel fuel energy.

Perhaps, the difference in the saw logs characteristics, physical properties, and number of logs does not have strong influence in the variation in energy consumption. As a result, the weak variability in the consumption of electrical and diesel fuel energy between the Light Red *Meranti* and Dark Red *Meranti* did not show any significant difference in the discharged amount of CO_2, CH_4, NO_x, N_2O, CO, and SO_2.

Potential Environmental Impact Assessment

The release of CO_2, CH_4, NO_x, N_2O, CO, and SO_2 is capable of impacting the environment (Kinjo *et al.* 2005; Eshun *et al.* 2011; Tellnes *et al.* 2012). Based on this fact, the potential environmental impacts were evaluated in this study, as Bovea and Gallardo (2006) pointed out that the output from the inventory study are normally not well defined in terms of environmental performance. Besides that, study based on inventory only proved to show unsupported conclusions. The findings of the potential environmental impacts are shown in Fig. 5.

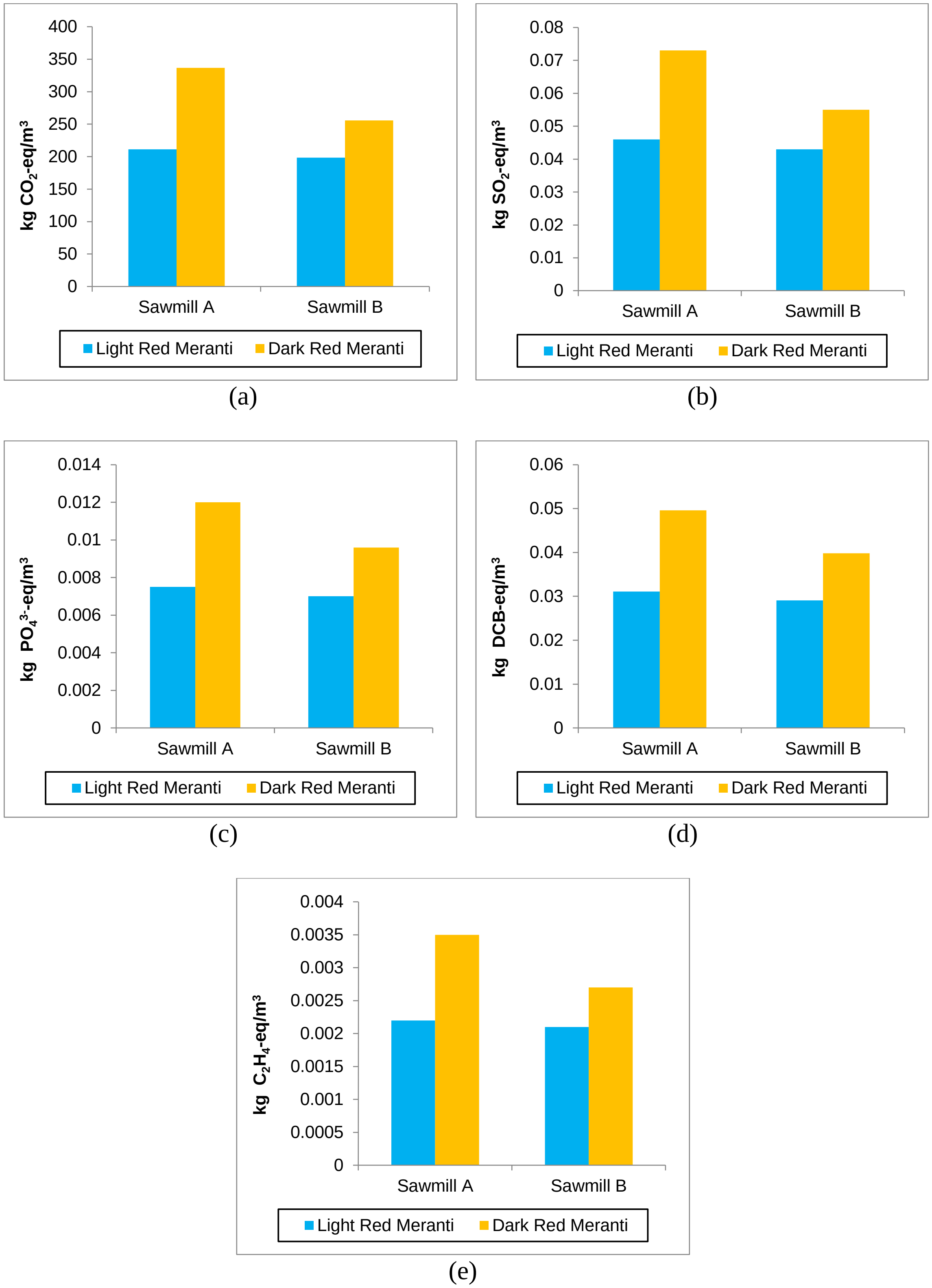

Fig. 5. Potential Environmental Impacts: (a) global warming potential of 100 years; (b) acidification potential; (c) eutrophication potential; (d) human toxicity potential; and (e) photo-oxidant formation potential

The findings in Fig. 5 indicate that the global warming, acidification, human toxicity, eutrophication, and photo-oxidant formation potentials showed a mean difference between the sawmills and wood species. A statistical analysis was performed in order to determine any significant difference for each of the potential environmental impacts between the test factors. As the normality for each of the potential environmental impacts was observed to be accepted, MANOVA statistical test was applied for further analysis.

The first part of the MANOVA test was a multivariate test. As shown in Table 15, the multivariate test for sawmill, wood species, and interaction of sawmill and wood species was not statistically significant, as the p-value was larger than 0.05. According to Leech (2005), the statistical analysis was not continued to examine in detail the univariate analysis for main effect of sawmill factor, main effect of wood species factor, and interaction of sawmill and wood species because the finding for each of the potential environmental impact would be non-significant as well. Hence, each of the potential environmental impacts was not significantly different between the main effect of sawmill factor, main effect of wood species factor, and interaction of sawmill and wood species.

Table 15. Multivariate Test of Variables on the Potential Environmental Impacts

	Wilks' Lambda value	F	Hypothesis df	Error df	*p*-value
Sawmill	0.923	0.727	2	26	0.545
Species	0.754	2.822	2	26	0.059*
Sawmill*species	0.924	0.708	2	26	0.556
*Significance accepted at the 0.05 level					

CONCLUSIONS

1. This study evaluated the environmental burden by applying the gate-to-gate concept for the sawmilling process. The environmental burdens were determined using the life cycle assessment (LCA) methodological framework for the two most common tropical hardwoods in Peninsular Malaysia, namely Light Red *Meranti* (*Shorea* spp.) and Dark Red *Meranti* (*Shorea* spp.) cut in two different sawmills.
2. The resource consumption of saw-logs and energy was evaluated in this study. The assessment of environmental burdens was carried out after determining the resource consumption measures. The discharged CO_2, CH_4, NO_x, N_2O, SO_2, and CO was enumerated from the energy consumption. Overall, the emission of CO_2 was the greatest, followed by SO_2, NO_x, and CO. The emission of CH_4 and N_2O from electrical energy and diesel fuel consumption was insignificant.
3. The components were transformed into several potential environmental impacts. The assessment of potential environmental impacts resulted in the potential formation of global warming (CO_2, CH_4, and N_2O), acidification (SO_2 and NO_2), human toxicity (NO_2 and SO_2), eutrophication (NO and NO_2), and photo-oxidant formation (CO, CH_4, SO_2, and NO_2).

4. The analysis showed that wood species, sawmill or the interaction between wood species and sawmill, respectively, had no significant influence on the environmental performance.

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