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Simulation of total dust emission from palm oil mills in Malaysia using biomass fuel composition and dust collector efficiency models

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Abstract

Palm oil mills are generally self-sufficient in terms of energy. However, burning of biomass fuel in a boiler has generated serious air pollution problem due to inappropriate boiler operation and inefficient dust collection system. This study aims to simulate the total dust emission from palm oil mills in Malaysia by modelling biomass fuel composition and dust collector efficiency. It has been found that before removal, the simulated average dust load after biomass boiler was 51.67 ± 5.39 g/s at a confidence level of 95%, and total dust load was 389,961 tonnes/year. Simulation values of total dust emission at different percentages of dust collector efficiency at 60%, 70%, 80%, 90% and 95% were 155,984, 116,988, 77,992, 38,996 and 19,498 tonnes/year, respectively. The simulation has also shown that dust concentration at a boiler outlet was 4.5 g/Nm^3. From the study, dust removal efficiency should be above 91% to ensure the compliance of dust concentration at 0.4 g/Nm^3 as prescribed by the Environment Quality (Clean Air) Regulations of 1978. Whereas in 2009, Sabah state has processed the most quantities of fresh fruit bunches, it has posed a potential impact on the environment and public in terms of total dust emission. Besides stack sampling that is used to monitor dust emission status, simulation can be a more simple way and an alternative to estimate the emission.

Keywords: Boiler, Biomass, Dust collector efficiency, Palm oil mill

Background

Malaysia is one of the largest palm oil producers in the world. However, the process of producing palm oil has generated million tonnes of empty fruit bunches, fibre and palm shell every year as wastes. Fibre and shell are mixed at certain ratios and used as fuel to generate energy to run the palm oil mill. Utilization of this palm waste as boiler fuel is creating a serious emission problem in the industry. The emissions are not only posing threat on human health, but also affecting agricultural crops, forest species and ecosystem [1-4]. Under the enabling legislation provided by the 1974 Environmental Quality Act, the Malaysian Government has issued the Environment Quality (Clean Air) Regulations, which came into force on 1 October 1978 and which limited air emissions from stationary fuel burning sources. For the palm oil industry, the principal concern of the regulation is toward the control of dark smoke and dust

emission from the burning waste, which are mixtures of fibre and shell. Under Regulations 21 and 25, the maximum permitted level of dust concentrations in gas emitted will be 0.5 g/Nm^3 before 1 October 1978 and a limit of 0.4 g/Nm^3 for plant erected after the date, expressed in terms of 12% CO_2.

A study conducted by Rozainee et al. [5] shows that the mean particulate concentration emitted from water-tube boilers equipped with and without particulate control equipment was 1.11 ± 0.58 g/Nm^3 and 1.93 ± 1.40 g/Nm^3, respectively, with only one of the boilers studied met the Department of Environment limits of 0.40 g/Nm^3 whilst others were still violating the standards. From another study by Rashid and Rozainee [6], it was found that the boilers, using palm waste as fuel at palm oil mills, are producing very much higher levels of dust emission of up to 11.6 g/Nm^3. According to De Kock and Yap [7], many dust collectors are installed without proper design and quality control procedures and many were simply copied from original suppliers. Dust collectors are often installed without verifying the performance during commissioning

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with only stack emission measurements carried out. By gross estimation, dust generated from typical 25 tonnes/h boiler combustion is around 4.5 g/Nm^3. Nowadays, most of the palm oil mill boiler operations are equipped with multi-cyclones to filter out the dust generated. For 60% of dust collection efficiency on average, it can be forecasted that the emission would be around 1.8 g/Nm^3 after the multi-cyclone, which create an estimated dust load of 450 tonnes/year.

In 2009, there were around 417 oil palm processing plants in the country [8] As compared with the number of mills in 1999, there are additionally more than 80 new mills that were put into operation as of today (over a span of 10 years). It is not difficult to foresee the air pollution from palm oil mill boilers that are yet to comply with the standard of 0.4 g/Nm^3, which is still continually creating a great burden to the local atmosphere. The palm oil industry has made a tremendous effort to increase its productivity over the past decades, but at the same time, the palm waste has also increased. Many studies focus on handling palm oil mill effluent or to maximize the utilization of biomass as renewable energy, yet there is lack of data and information about dust emission monitoring and follow-up as well as methods and technologies to lower emissions from biomass boiler.

Simulation of total dust emission can be used to estimate the trend of dust emission in the future and help in setting its reduction target for palm oil mills in Malaysia. It can also be used to facilitate decision-making processes that are related to air pollution control as part of emission inventory estimations. Therefore, the objective of this study is to estimate the total dust emission from palm oil mills in Malaysia from the perspectives of fuel compositions and efficiency of dust collection system to elucidate the air pollution problem that might have been neglected in the past. Simulation was carried out using several models: dust load and dust concentration model as well as dust collector efficiency. Dust load and dust concentration models are based on the composition of fibre and shell (Tables 1 and 2 and Figure 1), and the dust loading rate is calculated based on monthly average operation hours of a palm oil mill (Table 3). The selected efficiency range of dust collector was used to show the total dust emission rate, based on simulated dust load and dust concentration.

Methods

Source of emission

Baseline information collected from Malaysian Oil Palm Statistics 2009 [9] such as number of mills, fruit yield,

Table 1 Chemical composition on dry basis of fibre and shell

Element	Fibre	Shell	Fuel mixture of fibre and shell (simulated)
H (%)	6.0	6.3	6.09
C (%)	47.2	52.4	48.76
S (%)	0.3	0.2	0.27
N (%)	1.4	0.6	1.16
O (%)	36.7	37.3	36.88
Ash (%)	8.4	3.2	6.84

oil palm planted area and mill operation hours (Table 3) in every district of Malaysia in 2009 was used as input data for the simulation. Biomass boilers are often used to supply steam for palm fruit sterilization processes and turbines to generate power for plant operation. Due to the availability of adequate quantities of fibre and shell materials, which are used as solid fuel in the steam boiler, palm oil mills are generally self-sufficient in terms of energy. However, burning of biomass waste to generate energy has caused serious air pollution problem.

Generally, as suggested by USEPA, air pollutant emission can be estimated by using the following equation [10]:

$$E = A \times EF \times (1 - ER/100),$$

where, E = emissions, A = activity rate, EF = emission factor and ER = overall emission reduction efficiency as percentages.

Dust load model

Dust load can be defined as the concentration of solids in the inlet gas stream [11]. This study used the unit of mass flow, in gramme per second (g/s) for the dust load to show the loading rate to dust collector. The emission factor and the activity rate, which in this study refer to the fuel feeding rate to the boiler, were calculated in order to estimate the dust load.

The emission factor was determined by the amount of ash in gas flow and the ash content of palm oil biomass (fuel mixture of fibre and shell) in kilogramme of dust emitted per kilogramme of biomass burned. From Figure 1, it is found that the percentage of fibre and shell in fresh fruit bunches (FFB) are 13.5% and 5.5%, respectively [12] Therefore, the ratio of fibre and shell mixture in 1 kg of bulk fuel can be calculated by the following equations:
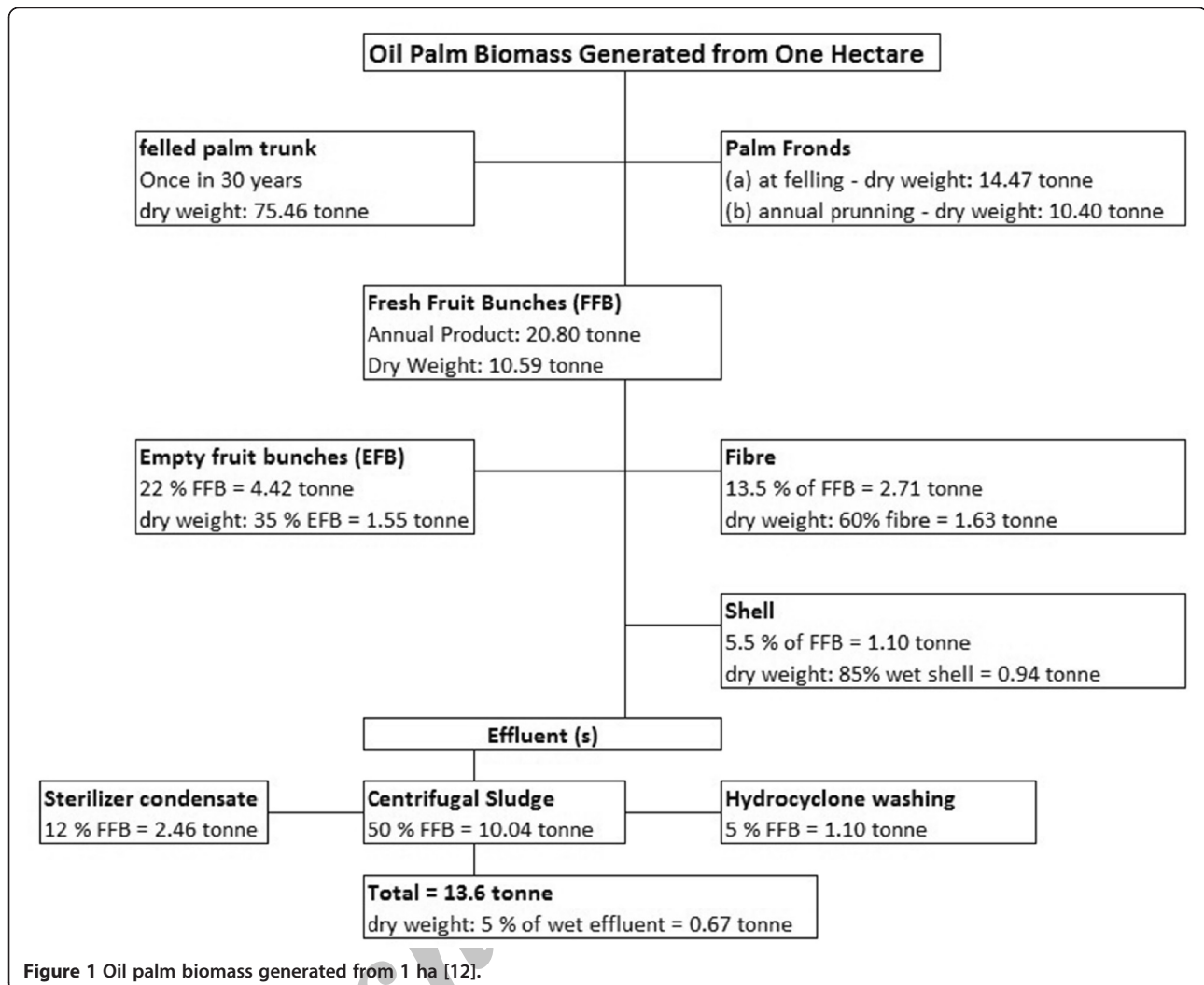
$$\text{Fibre mass} = \frac{\text{Percentage of fibre in FFB}}{(\text{Percentage of fibre in FFB} + \text{Percentage of shell in FFB})},$$

$$\text{Shell} = 1 - \left[\frac{\text{Percentage of fibre in FFB}}{(\text{Percentage of fibre in FFB} + \text{Percentage of shell in FFB})}\right].$$

Table 2 Calculation steps in determining dust concentration after biomass boiler

Step 1: From ultimate analysis, amount of oxygen required and air/fuel ratio were calculated[a]							Step 2: Calculated wet and dry composition of flue gas condition[b]								Step 3: Air volume was calculated based on ideal gas law at normal condition, and dust concentration was corrected to 12% carbon dioxide[c]		
Ultimate analysis on a dry basis	Mass (mass%)	Molar mass (kg/mol)	$\frac{\text{Mass (\%)}}{\text{Molar mass}}$ (mol/100 kg)	O_2 required	Product	mol/100 kg	From combustion/100 kg fuel (dry)				Wet composition		Dry composition		Per kilogramme of fuel	Dry	Wet
							Flue gas calculation	kmol	Molar mass	Mass	(mass%)	(vol.%)	(mass%)	(vol.%)			
Sulphur	0.27	32	0.0084	0.0084	SO_2	0.0084	H_2O	4.35	18	78	7.46	11.95			Ash (kg)	0.068	0.068
Hydrogen	6.09	2	3.045	1.5225	H_2O	1.5225	CO_2	4.06	44	179	17.05	11.16	18.42	12.68	Ash in flue gas (%)	50	50
Carbon	48.76	12	4.06	4.063	CO_2	4.06	SO_2	0.01	64	0.54	0.05	0.02	0.06	0.03	Fly ash (kg)	0.034	0.034
Oxygen	36.88	32	1.15	−1.153			N_2	25.96	28	727	69.31	71.34	74.90	81.02	Air volume at 0°C, 101.3 kPa (Nm^3)	7.2	8.2
Nitrogen	1.16	28	0.041				O_2	2.01	32	64.3	6.13	5.52	6.63	6.27	Dust concentration (g/Nm^3)	4.76	4.19
Ash	6.84						Total	36.39		1049					Regular standard carbon dioxide (vol.%)	12.0	12.0

[a]Amount of oxygen needed = 4.442; Theoretical air/fuel ratio (Af_{theo}) (kg air/kg fuel) = 6.125; Amount of excess air (%) = 50; Air/fuel ratio (kg air/kg fuel) = 9.19. [b]Excess water: from air = 18.38 kg/100 kg fuel, 1.021 mol/100 kg dry fuel; from fuel = 32.50 kg/100 kg fuel, 1.806 mol/100 kg dry fuel. [c]Corrected to carbon dioxide (both for dry and wet) = 4.51. (Adapted from "Fundamentals of Classical Thermodynamics, Third Edition," by Van Wylen, G.J., Sonntag, R.E., 1985. *Chapter 12: Chemical Reaction*, p.473. Wiley, Singapore).

Oil Palm Biomass Generated from One Hectare

felled palm trunk
Once in 30 years
dry weight: 75.46 tonne

Palm Fronds
(a) at felling - dry weight: 14.47 tonne
(b) annual prunning - dry weight: 10.40 tonne

Fresh Fruit Bunches (FFB)
Annual Product: 20.80 tonne
Dry Weight: 10.59 tonne

Empty fruit bunches (EFB)
22 % FFB = 4.42 tonne
dry weight: 35 % EFB = 1.55 tonne

Fibre
13.5 % of FFB = 2.71 tonne
dry weight: 60% fibre = 1.63 tonne

Shell
5.5 % of FFB = 1.10 tonne
dry weight: 85% wet shell = 0.94 tonne

Effluent (s)

Sterilizer condensate
12 % FFB = 2.46 tonne

Centrifugal Sludge
50 % FFB = 10.04 tonne

Hydrocyclone washing
5 % FFB = 1.10 tonne

Total = 13.6 tonne
dry weight: 5 % of wet effluent = 0.67 tonne

Figure 1 Oil palm biomass generated from 1 ha [12].

The following are the sample calculations:

$$\text{Fibre} = \frac{0.135}{(0.135 + 0.055)} = 0.7 \text{ kg},$$
$$\text{Shell} = 1\text{–}0.7 = 0.3 \text{ kg}.$$

Note that the ratio of fibre and shell (0.7 and 0.3 kg, respectively) may differ since shell is a valuable by-product that may be used in lower percentages as fuel.

From the chemical compositions on the dry basis of palm oil waste as shown in Table 1, the ash content for fibre and shell are 8.4% and 3.2%, respectively [3]. Hence, the ash content for the fuel mixture is estimated as follows:

$$\text{Ash percentage} = (\text{Fibre ash percentage} \times \text{Fibre mass}) + (\text{Shell ash percentage} \times \text{Shell mass}).$$

Here is its sample calculation:

$$\text{Ash percentage} = (8.4 \times 0.7) + (3.2 \times 0.3) = 6.84\%.$$

As most of the boiler firing systems like the suspension firing system and the fluidized bed combustion methods have very high dust entrainment (as high as 80%), older boiler design which uses spreader stoker has about 20% to 30% of the fuel being burned in suspension and thus has much less dust entrainment in the gas stream [13]. However, the data and statistics for the above boiler information are not available; it is assumed that the ash percentage in gas stream is 50%. Therefore, the emission factor can be calculated as follows:

$$\text{Emission factor} = 6.84\%\text{ash content} \times 50\%\text{in gas stream}$$
$$= 0.0342 \text{ kg dust/kg biomass}.$$

Dust generation rate from biomass fuel combustion in boiler can be estimated by taking into account the mill

Table 3 Monthly average operating hours of palm oil mill in 2009

State	January	February	March	April	May	June	July	August	September	October	November	December	Average
Johor	394.67	356.24	370.12	366.33	420.10	440.56	488.55	431.30	422.23	551.10	443.22	414.74	424.93
Kedah	397.85	420.37	433.33	395.53	423.66	476.69	577.16	494.81	487.94	524.84	409.82	382.10	452.01
Kelantan	267.27	229.19	276.91	297.33	270.71	274.28	306.10	336.82	331.53	445.99	303.30	319.32	304.90
Melaka	468.15	455.96	441.31	476.76	484.34	502.47	495.88	458.75	487.49	597.81	409.19	434.45	476.05
N. Sembilan	451.32	452.73	456.48	467.37	459.63	474.88	516.05	475.70	481.04	546.72	419.78	373.17	464.57
Pahang	360.60	334.92	387.06	362.92	402.57	394.19	429.87	433.29	428.28	534.00	411.32	371.16	404.18
Perak	367.52	368.36	402.74	404.09	451.18	464.65	516.41	447.19	425.13	505.99	402.46	411.48	430.60
P. Pinang	429.71	477.58	476.61	483.85	519.53	528.93	625.42	578.27	505.76	590.22	519.68	516.65	521.02
Selangor	379.15	386.27	406.49	414.12	404.52	447.80	472.55	391.97	391.25	457.88	393.20	371.47	409.72
Terengganu	333.48	273.77	348.10	332.15	344.54	327.55	421.18	413.03	421.53	588.35	437.59	424.55	388.82
P. Malaysia	384.97	375.54	399.92	400.05	418.08	433.20	484.92	446.11	438.22	534.29	414.96	401.91	427.68
Sabah	407.79	326.58	357.50	343.76	353.87	357.00	347.79	366.74	410.19	520.56	465.88	467.63	393.77
Sarawak	358.14	306.75	326.55	314.27	347.12	325.94	333.28	374.15	408.73	486.30	407.19	386.86	364.61
Sabah/Sarawak	382.97	316.67	342.03	329.02	350.50	341.47	340.54	370.45	409.46	503.43	436.54	427.25	379.19
Malaysia	384.64	365.73	390.27	388.21	406.81	417.91	460.85	433.50	433.43	529.15	418.55	406.13	419.60

Adapted from [8].

capacity as total fresh fruit bunches processed over a certain milling operation hours. By multiplying the mill capacity with the percentage of biomass generated from processed FFB, the biomass fuel feeding rate to the boiler can be estimated as follows:

$$\text{Fuel feed rate} = \frac{\text{Total FFB}}{\text{Mill operation hours}}$$
$$\times [(\text{Fibre percentage} \times \text{Dry weight percentage})$$
$$+ (\text{Shell percentage} \times \text{Dry weight percentage})].$$

This implies that the dust load equation can be deduced as follows:

$$\text{Dust load} = \text{Emission factor} \times \text{Fuel feed rate}.$$
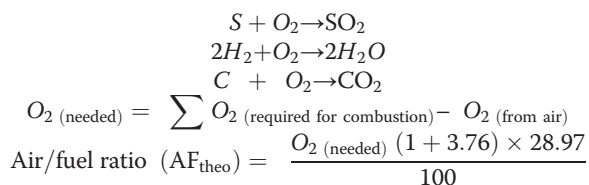
Statistical analysis

The average of total dust load is calculated to typify the overall situation of dust load per mill before the dust collector. In the future, any upgrade of mills or additional new mills in the country might contribute to the changes of the average dust load, which can be used to indicate the level of pollution source. Descriptive statistics was used to summarize the simulated average dust load. Furthermore, the normality of the data was tested using Anderson-Darling and Lilliefors test [14-16].

Dust concentration model

Dust concentration before the dust collector was simulated using ultimate analysis and air/fuel ratio calculation (Table 1). An example of the calculation for this model is shown in Table 2. A ratio of 70% fibre and 30% shell is applied for the mass percentage estimation in the ultimate analysis.

The combustion process involves the oxidation of constituents in the fuel that are capable of being oxidized [17] and can therefore be represented by chemical equations as follows:

$$S + O_2 \rightarrow SO_2$$
$$2H_2 + O_2 \rightarrow 2H_2O$$
$$C + O_2 \rightarrow CO_2$$
$$O_{2\ (\text{needed})} = \sum O_{2\ (\text{required for combustion})} - O_{2\ (\text{from air})}$$
$$\text{Air/fuel ratio } (\text{AF}_{\text{theo}}) = \frac{O_{2\ (\text{needed})} (1 + 3.76) \times 28.97}{100}$$

where 3.76 is the amount of N_2/O_2 in air (as a ratio), 28.97 is the mol mass of atmospheric air and calculation is based on 100 kg of fuel.

At normal conditions, air volume is calculated at 0°C, 101.3 kPa based on the ideal gas law:

$$V = \frac{nRT}{P},$$

where V = volume of gas (Nm^3), n = moles, R = universal gas constant, 8.314 J K^{-1} mol^{-1} and T = temperature (K).

Dust concentration before the dust collector is therefore calculated by mass of fly ash divided by air volume and corrected to 12% CO_2.

Dust collector efficiency

Even though the Malaysian Standard of Performance Evaluation for Mechanical Dust Collector has been introduced since 2003, implementation of the application is not as encouraged as expected. Moreover, as reported by De Kock and Yap [7], the performance of dust collectors installed at palm oil mills are generally low in efficiency due to improper design and lack of quality control as well as poor maintenance. The efficiency of a typical multicyclone after a biomass boiler can be as low as 40% only. This study simulates the dust emissions for dust collection system efficiencies of 60%, 70%, 80%, 90% and 95%.

Results and discussion
Results

Figure 2 shows the comparison of state total dust load. It can be seen that Sabah, Johor, Pahang, Sarawak and Perak are the states with significantly higher total dust load as compared with other states. Table 4 shows the results from districts of Malaysia based on simulated total mill capacity, total fuel feeding rate, total dust loading to dust collector and average dust load. The results were sorted from largest to smallest value of total dust load. The descriptive statistics, normality test and confidence interval of average dust load are reported in Table 5. The selected simulated data were found to be normally distributed ($p > 0.05$) based on Anderson-Darling and Lilliefors test, with the average dust load of 51.67 ± 5.39 g/s at a confidence level of 95%.

Table 6 shows the results for comparison of simulated state dust emission at 60%, 70%, 80%, 90% and 95% of dust removal efficiency. It is no doubt that the highest dust collector efficiency has the lowest outlet emission. The significant difference in values shows that whereas the lowest efficiency emitted 155,984 tonnes/year, the highest efficiency emitted only 19,498 tonnes/year. The relationship between simulated dust concentration and dust removal efficiency is shown in Figure 3. To achieve dust concentration with emission limit of 0.4 g/Nm^3, the removal efficiency should be above 91%.

Discussions
Dust load

From Figure 2, it was shown that while Johor, Pahang, Perak, Sabah and Sarawak are among the states that

Figure 2 Comparison of state total dust load in 2009.
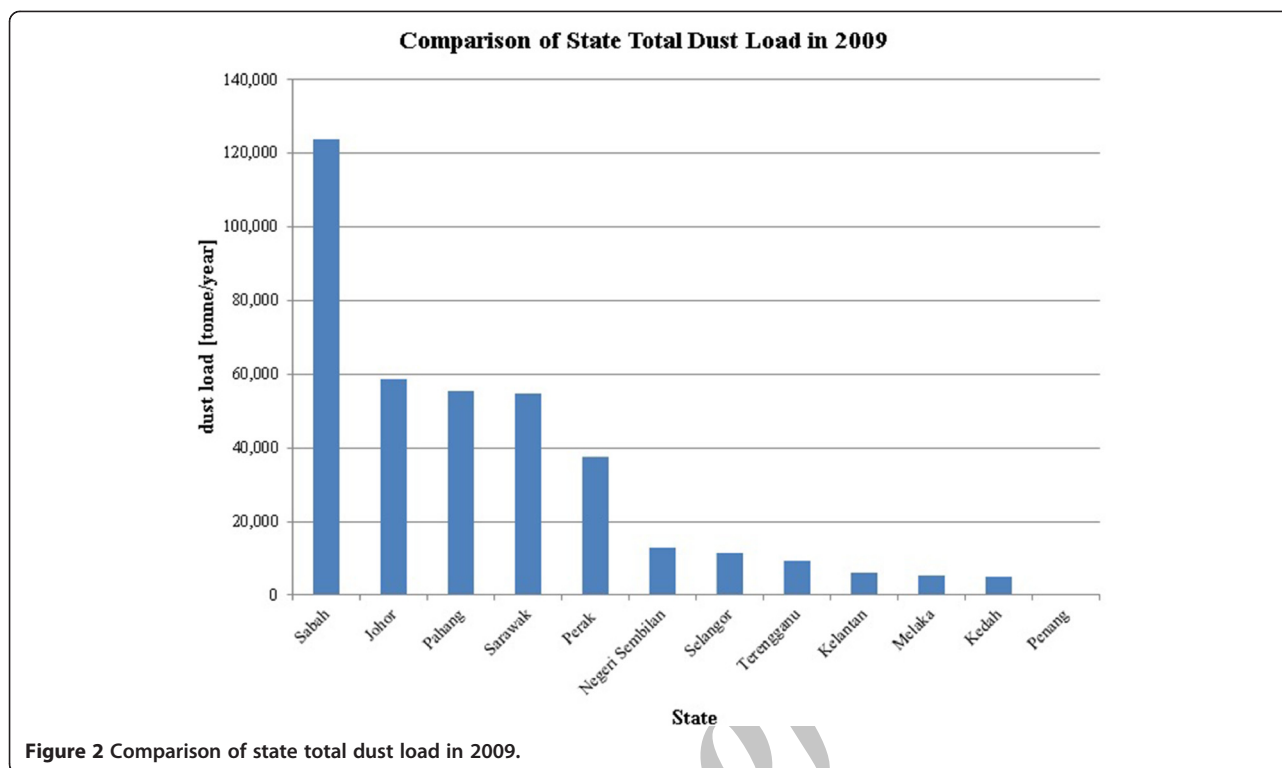
have the most quantities of mills, Sabah has the highest dust load among all states, which has a potential impact on the environment if not handled well. Due to the high processing rate of FFB, it is expected that more biomass fuel will be burned in boilers, thus resulting in higher dust load if compared with other states. The average dust load of 51.67 g/s from Tables 4 and 5 quantified the pollution source of a palm oil mill in 2009. Since there is no record of dust collector efficiency from palm oil mills in Malaysia, the average dust load can be used to estimate the overall emission from a range of dust collector efficiency. However, there is no limit stipulated by the Malaysia Environmental Quality Act 1974 for dust load, as a bigger mill definitely has higher dust load. Therefore, dust concentration is universally used as standard limit, although information of dust load is useful to track dust volume that has been released to the environment within a certain period of time, regardless of the size of a mill. Considering a case of two palm oil mills, 100 tonnes/h and the other is 50 tonnes/h, both emitting 0.4 g/Nm^3, they fall within the limit of the standard. However, dust load for the 100 tonnes/h mill (approximately 120 g/s) is double the dust load of 50 tonnes/h (approximately 60 g/s). This simply explains the pollution situation in a more direct way when compared to dust concentration.

From Table 6, at a different grade of dust removal efficiency, the total dust emission as simulated reduced drastically from 155,984 to 19,498 tonnes/year. This further

illustrates the importance of pollution control where pollution sources have increased because of new development without proper control; the consequence can be very serious. High emission trends from palm oil mills were believed that these have not been rectified for the past decades, thus the low dust removal efficiency.

Dust concentration
The simulated dust concentration at the boiler outlet was 4.5 g/Nm^3 at 12% CO_2. This is in agreement with the results reported in the literature. For wood-fired boilers, Buonicore and Davis [18] reported a value of 3,000 mg/Nm^3, whilst De Kock and Yap [19] reported that the boiler flue gas dust loads varied from 1490 to 4300 mg/Nm^3. These results were not corrected for carbon dioxide; hence, the dust load could have been higher after 12% CO_2 correction. Furthermore, it can be seen from Figure 3 that even a small difference in dust collection efficiency can make a significant difference in dust concentration. For example, at 95% efficiency, the dust concentration is 0.225 g/Nm^3, whereas at 90% efficiency, which is lower, the dust concentration is 0.450 g/Nm^3. The latter result will not comply with the Clean Air Regulation of 1978 at 0.4 g/Nm^3.

Efficiency of dust collection system
There are a few considerations that might cause lower efficiency in the dust collection system on boilers. One

Table 4 Simulated total mill capacity, total fuel feed rate, total dust load and average dust load

		Data from [8]				Simulation results			
State	District	Mill quantity	FFB yield	Planted area	Total capacity	Total mill capacity	Total fuel feed rate	Total dust load	Average dust load
			(tonnes/ha)	(ha)	(tonnes/year)	(tonnes/h)	(tonnes/h)	(g/s)	(g/s)
Sabah	Kinabatangan	30	21.73	348,450	7,571,819	1,602.40	204.71	1,944.72	64.82
Sabah	Lahad Datu	24	20.39	275,622	5,619,933	1,189.33	151.94	1,443.40	60.14
Sarawak	Miri	15	16.71	257,832	4,308,373	984.71	125.80	1,195.07	79.67
Sabah	Tawau	14	22.62	203,809	4,610,160	975.64	124.64	1,184.06	84.58
Sabah	Labuk Sugut	19	20.7	198,493	4,108,805	869.54	111.08	1,055.29	55.54
Sabah	Sandakan	14	21.32	168,660	3,595,831	760.98	97.21	923.54	65.97
Johor	Kluang	19	19.91	188,604	3,755,106	736.42	94.08	893.73	47.04
Pahang	Rompin	23	18.92	176,792	3,344,905	689.65	88.10	836.97	36.39
Sarawak	Bintulu	9	17.23	158,869	2,737,313	625.63	79.92	759.28	84.36
Perak	Hilir Perak	15	25.91	106,793	2,767,007	535.49	68.41	649.89	43.33
Johor	Kota Tinggi	15	17.17	145,050	2,490,509	488.42	62.40	592.75	39.52
Pahang	Bera	9	21.93	94,442	2,071,113	427.02	54.55	518.24	57.58
Johor	Segamat	9	19.70	102,048	2,010,346	394.25	50.37	478.47	53.16
Sarawak	Mukah	5	13.1	130,990	1,715,969	392.20	50.10	475.98	95.20
Pahang	Kuantan	9	18.54	89,916	1,667,043	343.71	43.91	417.13	46.35
Pahang	Pekan	6	20.47	78,377	1,604,377	330.79	42.26	401.45	66.91
Johor	Muar	5	22.17	68,802	1,525,340	299.14	38.21	363.04	72.61
Perak	Sri Manjong	3	27.18	54,088	1,470,112	284.51	36.35	345.29	115.10
Kelantan	Gua Musang	7	12.32	83,081	1,023,558	279.76	35.74	339.52	48.50
Johor	Batu Pahat	6	19.32	66,007	1,275,255	250.09	31.95	303.52	50.59
Terengganu	Kemaman	6	15.96	69,600	1,110,816	238.08	30.41	288.93	48.16
Johor	Johor Baru	5	18.42	65,256	1,202,016	235.73	30.11	286.09	57.22
Perak	Batang Padang	6	20.56	58,179	1,196,160	231.49	29.57	280.94	46.82
Pahang	Maran	7	17.88	60,888	1,088,677	224.46	28.67	272.41	38.92
Sabah	Kunak	7	21.98	47,930	1,053,501	222.95	28.48	270.58	38.65
Sarawak	Samarahan	4	13.31	64,679	860,877	196.76	25.14	238.79	59.70
Sarawak	Sibu	5	13.21	63,706	841,556	192.34	24.57	233.43	46.69
Perak	Perak Tengah	5	20.79	47,172	980,706	189.79	24.25	230.34	46.07
Pahang	Kuala Lipis	3	17.85	48,927	873,347	180.06	23.00	218.53	72.84
N. Sembilan	Jempol	5	18.21	53,498	974,199	174.75	22.32	212.08	42.42
Selangor	Kuala Selangor	5	25.05	33,614	842,031	171.26	21.88	207.85	41.57

Table 4 Simulated total mill capacity, total fuel feed rate, total dust load and average dust load (Continued)

Selangor	Kuala Langat	6	22.33	37,582	839,206	170.69	21.81	207.15	34.52
Pahang	Jerantut	4	19.49	38,626	752,821	155.22	19.83	188.37	47.09
Johor	Mersing	5	16.41	47,475	779,065	152.78	19.52	185.42	37.08
Sarawak	Kuching	3	15.43	41,417	639,064	146.06	18.66	177.27	59.09
Sabah	Semporna	4	23.24	28,734	667,778	141.32	18.05	171.51	42.88
Sarawak	Kapit	3	13.09	45,377	593,985	135.76	17.34	164.76	54.92
Sabah	Keningau	3	18.75	31,756	595,425	126.01	16.10	152.93	50.98
N. Sembilan	Port Dickson	2	23.8	29,399	699,696	125.51	16.03	152.32	76.16
N. Sembilan	Tampin	3	19.85	34,500	684,825	122.84	15.69	149.08	49.69
Melaka	Jasin	2	25.14	26,749	672,470	117.72	15.04	142.87	71.43
Perak	Kuala Kangsar	2	22.89	25,289	578,865	112.03	14.31	135.96	67.98
Perak	Krian	4	21.53	26,197	564,021	109.15	13.94	132.47	33.12
Kedah	Kulim	3	21.95	25,762	565,476	104.25	13.32	126.52	42.17
Terengganu	Dungun	2	12.75	36,894	470,399	100.82	12.88	122.36	61.18
Sarawak	Betong	1	14.01	29,086	407,495	93.14	11.90	113.03	113.03
Pahang	Temerloh	3	10.75	40,924	439,933	90.70	11.59	110.08	36.69
Pahang	Raub	3	17.78	24,323	432,463	89.16	11.39	108.21	36.07
Melaka	Alor Gajah	1	22.4	22,697	508,413	89.00	11.37	108.01	108.01
Pahang	Bentong	3	19.1	22,452	428,833	88.42	11.30	107.30	35.77
Selangor	Ulu Selangor	4	18.81	22,610	425,294	86.50	11.05	104.98	26.24
Johor	Pontian	1	14.44	29,206	421,735	82.71	10.57	100.37	100.37
Perak	Larut Matang	8	20.69	20,505	424,248	82.10	10.49	99.64	12.46
Perak	Kinta	1	22.59	16,075	363,134	70.28	8.98	85.29	85.29
Sabah	Beaufort	2	12.82	24,614	315,551	66.78	8.53	81.05	40.52
Selangor	Sepang	4	17.26	18,691	322,607	65.61	8.38	79.63	19.91
Sarawak	Sri Aman	1	9.58	29,606	283,625	64.82	8.28	78.67	78.67
N. Sembilan	Seremban	3	19.68	17,635	347,057	62.25	7.95	75.55	25.18
Terengganu	Ulu Terengganu	3	12.97	20,916	271,281	58.14	7.43	70.56	23.52
Kedah	Baling	1	22.29	13,112	292,266	53.88	6.88	65.39	65.39
Terengganu	Setiu	1	13.19	18,382	242,459	51.96	6.64	63.07	63.07
Kelantan	Kuala Krai	2	15.27	11,933	182,217	49.80	6.36	60.44	30.22
Kedah	Bandar Bahru	2	23.22	10,880	252,634	46.58	5.95	56.53	28.26
N. Sembilan	Jelebu	1	18.09	14,216	257,167	46.13	5.89	55.98	55.98

Table 4 Simulated total mill capacity, total fuel feed rate, total dust load and average dust load *(Continued)*

Perak	Selama	1	18.27	12,215	223,168	43.19	5.52	52.42	52.42
Sarawak	Limbang	1	14.68	12,452	182,795	41.78	5.34	50.70	50.70
Kelantan	Tanah Merah	1	13.82	10,377	143,410	39.20	5.01	47.57	47.57
Sabah	Tenom	1	20.35	5,695	115,893	24.53	3.13	29.77	29.77
Selangor	Klang	2	18.03	6,261	112,886	22.96	2.93	27.86	13.93
Selangor	Petaling	1	22.28	4,737	105,540	21.47	2.74	26.05	26.05
Sabah	Kota Marudu	2	11.71	8,293	97,111	20.55	2.63	24.94	12.47
Penang	S. Prai Selatan	2	15.35	6,863	105,347	16.85	2.15	20.45	10.22
Terengganu	K. Terengganu	1	9.24	3,901	36,045	7.73	0.99	9.38	9.38
Other districts without palm oil mills				120,497	2,114,759				
Malaysia	Total mills	417		4,685,085	89,255,221	17,726.34	2,264.54	21,513.1	51.67

Table 5 Descriptive statistics, normality test and confidence interval of average dust load

Selected data	Average dust load (g/s)
Size	73
Mean	51.6696
Standard deviation	23.5164
Range	9.38 to 115.10
Skewness	0.6285
Kurtosis	0.4650
Normality test	
Anderson-Darling	score = 0.6528
(*p* value)	$(0.05 = < p < 0.10)$
Lilliefors D = max [D−, D+]	0.0871 = max [0.0440, 0.0871]
(*p* value)	$(0.15 = < p < 0.20)$
Confidence interval (95%)	51.67 ± 5.39 g/s

of the reasons is the deterioration of a dust collection system. Even properly designed systems from reputable suppliers may show a decrease in performance characteristics due to wear and poor maintenance. In principle, the dust collector is like any other equipment, requiring regular maintenance, servicing, evaluation and testing to ensure its operation is efficient and optimal. Poor awareness among the millers who only focus on maximizing mill productivity and who try to minimize the cost of production, instead of investing in high-efficiency pollution control system and good maintenance practice to protect the environment, is a major concern. The reason might be that there is no return or profit from the investment; it is merely a requirement of the Clean Air Regulation of 1978. Because of this, many mills simply use low-cost dust collectors just to fulfil the basic requirement of having a solid fuel boiler. Furthermore, improper design of dust collection systems, including poor quality control of material, can shorten the lifespan or increase the deterioration rate of a dust collection system, or it might even escalate the problem. For example, putting a wet scrubber instead of dry mechanical cyclone after a biomass boiler might create further problem since wastewater needs an extra wastewater treatment system to prevent water pollution problems.

Dust particle size

Dust particle size is one of the critical factors that must be carefully considered when designing a mechanical dust collector. A properly designed filter will be able to take out finer particles from the gas stream and will result in a lower dust concentration at the stack. A poorly designed dust collector will not be able to capture fine particles, thus affecting its overall efficiency.

Boiler operation

Under normal operating conditions in a palm oil mill, the boiler plant is subjected to fluctuating loads which are accompanied by variables. These fluctuating loads are inherent in the process plant operation and are the main cause for lowered boiler efficiency, which directly influence the air pollution problem, production capacity in terms of throughput of fresh fruit bunches, products recovery efficiency and the quality of products produced [20]. This means that if the boiler efficiency is low, it might need a higher load of fuel to heat up the boiler itself in order to get the required steam demand. When fuel feeding rates increase, more ash will be generated from fuel combustion, resulting in higher dust loads to the dust collection system, hence higher dust emission to the atmosphere. Therefore, it is critical for millers to make sure the boiler operation is always at optimal conditions.

Fuel conditioning

In older boilers, inefficient combustion is due to the condition of fuel which is mostly wet and lumpy, inconsistent fuel feeding and poor fuel distribution on the furnace grate of boiler. Pre-conditioning of fuel can help in better combustion in the boiler and increase the boiler efficiency, at the same time, eliminating dark smoke. Due to the increased combustion efficiency, the carbon dioxide content will be increased, resulting in lower dust emission when expressed in terms of 12% CO_2 [21,22].

Performance evaluation and reduction target

The performance evaluation of mechanical dust collector (MS 1723: 2003) involves simultaneous isokinetic measurements at the inlet and outlet of the dust collector in order to determine the actual dust collection performance characteristic of the system installed. This performance characteristic as measured can be used for verifying the design specifications. After the performance characteristic has been determined, future measurements will show if any deterioration has taken place. These measurements should be part of the maintenance programme of the mill. This will assist not only in ensuring that the emission complies with the set of standards, but also in planning maintenance work on dust collector in advance. Evaluation results should be kept as records by state branches under the Department of Environment. Establishing a databank is not only for performance evaluation and monitoring purpose, but also for the identification of inefficient systems so that action can be taken to control the pollution. Setting a short-term or long-term reduction target can help to improve dust emission. For example, with reference to Table 6, by knowing the current status of the industry's

Table 6 Comparison of simulated state total dust emission at different dust removal efficiency

State	Before removal	District dust emission (tonnes/year)				
	(tonnes/year)	60%	70%	80%	90%	95%
Sabah	123,870	49,548	37,161	24,774	12,387	6,194
Johor	58,805	23,522	17,641	11,761	5,880	2,940
Pahang	55,502	22,201	16,651	11,100	5,550	2,775
Sarawak	54,924	21,969	16,477	10,985	5,492	2,746
Perak	37,431	14,973	11,229	7,486	3,743	1,872
Negeri Sembilan	12,945	5,178	3,884	2,589	1,295	647
Selangor	11,567	4,627	3,470	2,313	1,157	578
Terengganu	9,310	3,724	2,793	1,862	931	466
Kelantan	5,895	2,358	1,768	1,179	589	295
Melaka	5,159	2,064	1,548	1,032	516	258
Kedah	4,851	1,941	1,455	970	485	243
Penang	460	184	138	92	46	23
Malaysia	389,961	155,984	116,988	77,992	38,996	19,498

total emission of 155,984 tonnes/year at overall efficiency of 60% and considering the industry and its affordability in terms of profit, the most cost-effective solution available can be recommended and a target can be set at increasing the efficiency to 95% to reduce the emission to 19,498 tonnes/year.

Conclusions

This study has proven that simulation can be used as an alternative to estimate dust emission and recommends that the minimum efficiency for a dust collector required for a boiler besides actual measurement be done on the stack. However, regular measurement of the dust collector performance, which can be done by simultaneous isokinetic measurements at the inlet and outlet of the dust collector, is critical to accurately identify the problem so that subsequent action can be taken to overcome it.

Issues such as factors that affect dust collector efficiency, boiler operation, fuel conditioning, performance evaluation and reduction target have been discussed. Unless proper implementation and necessary improvement of the above actions have been taken, high dust emission will continue to pose serious problems to the industry and environment.
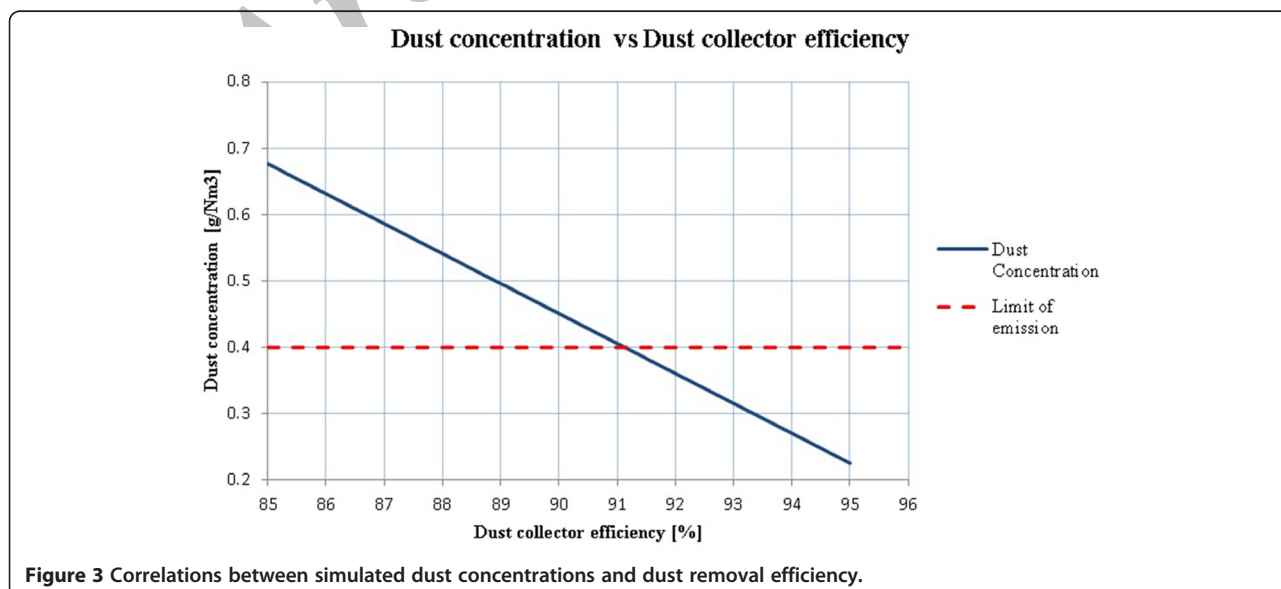
Figure 3 Correlations between simulated dust concentrations and dust removal efficiency.

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