Environmental load assessment for an integrated design of microalgae system of palm oil mill in Indonesia

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Tables

Table 1 - General information of a selected mill in Riau province, Indonesia from a field survey in 2014

	Parameters	Description
1.	Average rainfall*	2,870 mm $year^{-1}$
2.	Evaporation*	1,460 mm $year^{-1}$
3.	Average local temperature*	27^{o}C (in the range of 22 – 34^{o}C)
4.	Solar radiation*	17 MJ $m^{-2}d^{-1}$
5.	Size of a plantation (not include the small landholders' plantations)**	10,630 ha
6.	Original land cover**	Flat land area with average 89.20% arable land and 10.80% peat soil
7.	Re-planting**	25 years
8.	Productive lifetime**	21 years (4 years of nursery)
9.	Mill capacity**	60 tons FFB h^{-1}
10.	Mill operation**	330 d $year^{-1}$
11.	Annual FFB processing***	200,000 tons
12.	Annual CPO production***	40,000 tons
13.	Edible oil : biodiesel production (own scenario)	50:50
14.	Mill extraction process***	0.5 – 1.5 m^3 POME $tons^{-1}$ FFB or 2.5 – 3.5 m^3 POME $tons^{-1}$ CPO
15.	POME generated***	20,000 m^3 $month^{-1}$
16.	Potential solid waste from mill***	90,000 tons $year^{-1}$

* Local meteorological station (30 years basis data)

** Palm oil mill information

*** Field measurement

Table 2 - Measured CNP nutrients in POME and balance for microalgae culture

Nutrients	Available nutrients (concentration-based) [mg L^{-1}]	Average available nutrients from POME [ton $ha^{-1}year^{-1}$]	Additional nutrients due to of shortage [ton $ha^{-1}year^{-1}$]	Additional nutrients (mass-based) [%]	Total nutrients [ton $ha^{-1}year^{-1}$]	Approximate or minimum nutrients ratio based on the Redfield ratio*
C	964.28±241.00	23.15±5.79	44.07±11.02	65.56	67.22±16.80	56.0
N	269.58±67.39	6.47±1.62	2.17±0.54	25.12	8.64±2.16	7.2
P	68.40±17.10	1.64±0.41	-	-	1.20 (precipitated)	1.0

*Calculated based on possible Redfield ratio **[13, 24, 25, 38, 41, 42]**

Table 3 - Materials and energy balances for palm oil-based biodiesel production

Material and process input kg^{-1}-biodiesel		Plantation and mill (average data for the Riau site, Indonesia)			
		Material [kg]	**Energy [MJ]**	**CO_2eq [kg]**	**Water [m^3]**
Cultivation					
a) Nursery phase (4 years)	[kg $ha^{-1}y^{-1}$]				
N fertilizer (Urea)	14.67	2.60×10^{-3}	0.08	1.30×10^{-3}	3.67×10^{-7}
P fertilizer (TSP)	7.67	1.65×10^{-3}	0.01	6.59×10^{-4}	9.97×10^{-7}
K fertilizer (NPK)	21.95	4.59×10^{-3}	0.03	1.83×10^{-3}	9.91×10^{-7}
Mg fertilizer (MgO)	5.04	0.01×10^{-1}	0.02	0.01×10^{-1}	9.19×10^{-7}
Glyphosate	2.50	5.36×10^{-4}	ND	0.05	ND
Cypermethrin	1.20	2.57×10^{-4}	ND	0.03	ND
Chlorothalonil	0.274	5.88×10^{-5}	ND	5.79×10^{-3}	ND
Warfarin	0.21×10^{-3}	4.51×10^{-8}	ND	4.44×10^{-6}	ND
Paraquat	0.75	1.61×10^{-4}	ND	0.02	ND
b) Mature phase (21 years)					
KCl (NPK 0-0-60)	239.24	0.05	0.28	0.03	1.08×10^{-5}
NPK compound (NPK 15-15-15)	247.20	0.05	0.47	0.04	3.39×10^{-5}
K_2SO_4 (NPK 0-0-50)	0.75	0.02×10^{-2}	0.06×10^{-2}	3.46×10^{-5}	9.97×10^{-8}
Diammonium Phosphate (DAP) $(NH_4)_2HPO_4$	5.20	0.01×10^{-1}	0.02	0.01×10^{-1}	9.19×10^{-7}
Phosphate rock (32% P_2O_5, 50% CaO)	12.07	0.03×10^{-1}	0.03×10^{-1}	0.02×10^{-2}	2.12×10^{-8}
Single Superphosphate (SSP) 35% $Ca(H_2PO_4)_2$	13.09	0.03×10^{-1}	0.08×10^{-1}	0.05×10^{-2}	1.39×10^{-7}
Triple Superphosphate (TSP) 80% $Ca(H_2PO_4)_2$	46.55	0.01	0.07	0.04×10^{-1}	6.05×10^{-6}
Urea, 100% $CO(NH_2)_2$ (NPK 46.6-0-0)	112.63	0.02	0.58	0.02	2.82×10^{-6}
Lime fertilizer	400.00	0.08	0.06	0.03×10^{-1}	0.11×10^{-3}
Ammonium sulfate, $(NH_4)_2SO_4$	144.96	0.03	0.31	0.02	1.70×10^{-6}
Organic compost	538.00	1.15×10^{-3}	-	0.03	-
Diesel fuel (machinery)	-	0.02	1.11	0.09	9.33×10^{-6}
	[m^3-water $ha^{-1}y^{-1}$]				
Water from nature	58,029.30	3.10	-	-	3.10
Irrigation	160.14	8.59×10^{-3}	0.23	0.03	0.15×10^{-1}
Wastewater	37.81	2.03×10^{-3}	-0.12	-0.01	-0.33×10^{-1}
Sub-total			**3.16**	**0.45**	
Harvest/extraction – option (a)					
Diesel fuel (machinery)			0.01×10^{-2}	9.16×10^{-6}	1.14×10^{-9}
Transportation (10-20 tons)		5.7×10^{-5}	0.03×10^{-2}	2.23×10^{-5}	2.79×10^{-9}
Processing water		5.70	0.02	0.04	0.02
CPO mill electricity			0.04	0.04×10^{-1}	0.78×10^{-2}
PKO mill electricity			0.03	0.03×10^{-1}	0.59×10^{-2}
Landfill (EFB)		0.79	0.82	0.39	0.24×10^{-3}
Landfill (shell)		0.27	0.21	0.10	8.01×10^{-5}
Landfill (fiber)		0.53	0.51	0.24	0.16×10^{-3}
POME treatment		5.89	1.36	0.46	0.54×10^{-2}
Methane emission from POME		-	-	0.9	-
Sub-total – option (a)			**2.99**	**2.14**	
Conversion					
Methanol		0.16	5.48	0.10	0.09
Methanol recovery		-0.07	-2.39	-0.04	-0.04
Glycerin		-0.04	-0.48	-0.12	-0.03
NaOH (50%)		0.01	0.12	0.07×10^{-1}	0.47×10^{-4}
H_3PO_4 (75%)		0.09×10^{-2}	0.05×10^{-1}	0.03×10^{-2}	0.67×10^{-6}
Processing water		1.40	0.05×10^{-1}	0.09×10^{-2}	0.02×10^{-1}
Wastewater treatment		1.45	0.16	0.05	-0.02×10^{-1}
Diesel fuel (machinery)		0.02	1.13	0.02	0.07×10^{-1}
Electricity			0.02	0.15×10^{-1}	0.03×10^{-1}
Sub-total			**4.05**	**0.03**	
Total			**10.20**	**2.62**	
Measured calorific value (CV) of palm oil based biodiesel [MJ kg^{-1}]		**39.60**			
Energy-Profit Ratio (EPR) [-]		**3.88 = (39.60/10.20)**			

Table 4 - Materials and energy balances of microalgae-based biodiesel production

Material and process input kg^{-1}-biodiesel	Mixed culture			
	Material [kg]	**Energy [MJ]**	**CO_2eq [kg]**	**Water [m^3]**
Cultivation [13, 24 - 26, 38, 41, 42]				
Flue gases (12.75% CO_2)	56.83	-	-7.25	-
POME utilization	1,076.23	-17.98	-3.81	-1.07
Urea (as N fertilizer)	0.20	12.93	0.72	2.56×10^{-5}
Freshwater supply (make-up water)	270	0.96	0.04	0.27
Paddlewheel **[43]**		3.88	0.65	0.03
POME pump in **[13]**		0.36	0.06	0.02×10^{-1}
Blower (flue gases injection)		0.23	0.04	0.01×10^{-1}
Sub-total		**0.38**	**-9.55**	
Harvest/extraction [4, 44 - 47]				
Alum sulfate (flocculant)	1.00	10.40	0.73	1.99
Sodium silicate (de-flocculant)	2.50	58.30	3.98	10.20
Alum sulfate recovery (70%)	-0.70	-7.28	-0.44	-1.40
Sodium silicate recovery (70%)	-1.75	-40.81	-2.39	-8.12
Transfer pump		0.36	0.06	0.02
Belt filter press		0.72	0.12	0.36×10^{-1}
Sonication (cell lysing)		5.16	0.86	0.03
Hexane extraction	6.66	138.53	2.24	2.28
Hexane recovery (98%)	-6.53	-135.76	-2.20	-2.24
Electric dryer		0.16	0.03	0.08×10^{-1}
Heat recovery for drying process		-6.01	-0.59	0.24
Sub-total		**23.77**	**2.40**	
Conversion				
Methanol	0.16	5.48	0.10	0.09
Methanol recovery	-0.07	-2.39	-0.04	-0.04
Glycerin	-0.04	-0.48	-0.12	-0.03
NaOH (50%)	0.01	0.12	0.07×10^{-1}	0.47×10^{-4}
H_3PO_4 (75%)	0.09×10^{-2}	0.05×10^{-1}	0.03×10^{-2}	0.67×10^{-6}
Processing water	1.40	0.05×10^{-1}	0.09×10^{-2}	0.02×10^{-1}
Wastewater treatment	1.45	0.16	0.05	-0.02×10^{-1}
Diesel fuel (machinery)	0.02	1.13	0.02	0.07×10^{-1}
Electricity		0.02	0.15×10^{-1}	0.03×10^{-1}
Sub-total		**4.03**	**0.03**	
Total		**28.18**	**-7.12**	
Measured calorific value (CV) of microalgae based biodiesel [MJ kg^{-1}]	**36.76**			
Energy-Profit Ratio (EPR) [-]	**1.30 = (36.76/28.18)**			

Table 5 – Estimated real nutrients substitution and the contribution to energy and CO_2eq footprint

Compound added	MR (molecular ratio) from chemical compounds	Real nutrients weight needed [tons $ha^{-1}year^{-1}$]	Contribution to	
			energy footprint [GJ $ha^{-1}year^{-1}$]	CO_2eq footprint [tons $ha^{-1}year^{-1}$]
Carbon source				
Flue gases (12.75% weight CO_2)	Flue gas mass component CO_2: 12.75%weight N_2: 73.15% weight O_2: 3.70%weight H_2O: 10.39%weight	= (100/12.75) × 161.59±40.41 **= 1,267.37 ±316.94**	-	**-161.59±40.41**
CO_2 (pure)	44	= (44/12) × 44.07±11.02 = 161.59±40.41		
Option for Nitrogen sources				
Urea (CH_4N_2O)	60	= (60/28) × 2.17±0.54 = **4.65±1.16**	[62 MJ kg^{-1}]**[4]** **288.3±71.92**	[3.45 kg CO_2eq kg^{-1} **16.04±4.00**
Sodium Nitrate ($NaNO_3$)	85	= (85/14) × 2.17±0.54 = **13.18±3.28**	[37.8 MJ kg^{-1}]**[4]** **498.20±123.98**	[4.71 kg CO_2eq kg^{-1}] **62.08±15.45**
Ammonia (NH_3)*	17	= (17/14) × 2.17±0.54 = **2.64±0.66**	[34.8 MJ kg^{-1}]**[4]** **91.87±22.97**	[1.78 kg CO_2eq kg^{-1}] **4.69±1.17**
*Increasing the ammonia content in POME in one side will bring additional benefit to reduce the fertilizer need				
Phosphorus source				
Phosphate fertilizer (P_2O_5)	142	= (142/62) × -1.64±0.41 = **-3.76±0.94**	[-27.9 MJ kg^{-1}] **[4]** **-104.90±26.23**	[-2.24 kg CO_2eq kg^{-1}] **-8.42±2.11**

Table 6 - Summary of GHG emissions for each bioenergy source

	Bioenergy source	Total capacity per year	Specific GHG emissions	Total CO_2eq emission [ton-CO_2eq year^{-1}]	Additional CO_2eq [kg-CO_2eq kg^{-1}-biodiesel]	CO_2eq offset from fossil fuel net-CO_2eq reduction [ton-CO_2eq year^{-1}]
(a)	Palm oil based biodiesel - without treated POME and landfill (60 tons-FFB h^{-1})	26,248 tons	2.62 kg-CO_2eq kg^{-1}-palm oil based biodiesel	68,770	Baseline	18,333 (21.05% lower)*
(b)	Biomass power plant (shell and fibers) for 4.5 MW	35,640 MWh	368 kg-CO_2eq per MWh **[60]**	13,116	0.49	13,881 (51.42% lower)**
(c)	Biogas power plant (POME) for 1.2 MW	9,504 MWh	33 kg-CO_2eq per MWh **[58]**	314	0.012	6,885 (95.42% lower)**
(d)	Microalgae based biodiesel (POME + 25% urea + flue gases) for 10 ha	223 tons	-7.12 kg-CO_2eq kg^{-1}-microalgae based biodiesel	-1,588	-0.06	2,275 (331.15% lower)*
	Total			**80,612**		

*Standard of diesel fossil fuel emission (2016) is about 83.8 g-CO_2eq MJ^{-1} **[54, 58-60]**
Indonesia power emission factor (2016) is around 757.5 kg-CO_2eq per MWh **[36]