

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°C (in the range of 22 – 34°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 ₂ eq [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 ₂ SO 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) ₂ HPO ₄	5.20	0.01×10 ⁻¹	0.02	0.01×10 ⁻¹	9.19×10 ⁻⁷
Phosphate rock (32% P ₂ O 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 ₂ PO 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 ₂ PO 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) ₂ SO 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 ₃ PO 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 ₂ eq [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 ₃ PO 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 CO₂eq 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 ₂ eq 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 ₂ O: 10.39% weight	= (100/12.75) × 161.59±40.41 = 1,267.37 ±316.94	-	
CO ₂ (pure)	44	= (44/12) × 44.07±11.02 = 161.59±40.41		-161.59±40.41
Option for Nitrogen sources				
Urea (CH ₄ N ₂ O)	60	= (60/28) × 2.17±0.54 = 4.65±1.16	[62 MJ kg ⁻¹][4] 288.3±71.92	[3.45 kg CO ₂ eq 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 ₂ eq 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 ₂ eq 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 ₂ O 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 ₂ eq 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 ₂ eq emission [ton-CO ₂ eq year ⁻¹]	Additional CO ₂ eq [kg-CO ₂ eq kg ⁻¹ -biodiesel]	CO ₂ eq offset from fossil fuel net-CO ₂ eq reduction [ton-CO ₂ eq year ⁻¹]
(a) Palm oil based biodiesel - without treated POME and landfill (60 tons-FFB h ⁻¹)	26,248 tons	2.62 kg-CO ₂ eq 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 ₂ eq 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 ₂ eq 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 ₂ eq 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-CO₂eq MJ⁻¹ [54, 58-60]

**Indonesia power emission factor (2016) is around 757.5 kg-CO₂eq per MWh [36]