

Supporting Information

Red palm oil versus conventionally refined palm oil: a cradle-to-gate carbon footprint on mass, carotene and vitamin A functional units

Ahmad Nur Sidiq, Devi Ardila, Chesy Sripratiwi, Yuni Erlinda,
Jafar Arifin, and Muhammad Naufan Rizqullah

Contents: Section S1, deodorization energy model; S2, process scale and heat source scenarios; S3, deacidification mass balance, chemicals, water and transport; S4, grid emission factor; S5, vitamin A conversions; Tables S1–S5. All values are printed by the calculation scripts, which are available from the corresponding author on request.

S1 Deodorization energy model

Riyadi et al.¹ report the deodorization stage in full except for its energy consumption. The unit is a horizontal cylindrical SS 316 batch deodorizer of 100 L nominal capacity with internal electric heating elements, a shell-and-tube condenser and a rotary vacuum pump. A 100 kg charge of NRPO is stirred at 46 °C, heated to 140 °C at 20 mmHg with nitrogen sparging at 20 L h⁻¹, held for 1 h and cooled under vacuum to below 60 °C.

Heater duty is the sum of the sensible heat of the charge,

$$Q_{\text{sens}} = m c_{p,\text{oil}} (T_{\text{deod}} - T_{\text{start}}) (1 - \eta_{\text{HR}}), \quad (\text{S1})$$

the latent heat of water evaporated from the charge, $Q_{\text{lat}} = m w_{\text{H}_2\text{O}} \Delta h_{\text{vap}}$, and vessel heat loss over heat-up and hold,

$$Q_{\text{loss}} = UA \left[\overline{\Delta T}_{\text{heat}} t_{\text{heat}} + \Delta T_{\text{hold}} t_{\text{hold}} \right], \quad (\text{S2})$$

where A follows from the vessel volume at $L/D = 2$. Heater electricity is $(Q_{\text{sens}} + Q_{\text{lat}} + Q_{\text{loss}})/\eta_{\text{heater}}$ with $\eta_{\text{heater}} = 0.95$; heat recovery η_{HR} is zero in the pilot case.

Vacuum pump power is sized from the non-condensable gas load, sparged nitrogen and air in-leakage, expanded to 20 mmHg at the 40 °C condenser outlet:

$$S = \frac{\dot{n}_{\text{N}_2} + \dot{n}_{\text{leak}}}{p_{\text{op}}} R T_{\text{pump}}, \quad P_{\text{vac}} = f_s S p_{\text{spec}}. \quad (\text{S3})$$

With an air in-leakage of 0.10 kg h⁻¹ the gas load is 4.2 m³ h⁻¹ (0.81 nitrogen, 3.37 air); a sizing

factor of 2.0 and a specific power of $0.11 \text{ kW (m}^3 \text{ h}^{-1})^{-1}$ give 0.92 kW, run for 3 h because cooling is also under vacuum. Oil pump, cooling-water pump and cryogenic nitrogen production are included at rated power and operating time. The pilot batch requires 9.44 kWh (Table S1).

Two source inconsistencies are carried forward. The vessel is specified at 100 L but charged with 100 kg of oil, about 112 L at 46 °C, so heat loss is understated. The NRPO characterized as deodorizer feed (535.64 mg kg⁻¹ carotene, 0.484% FFA) is not the NRPO produced in the deacidification study (464.96 mg kg⁻¹, 0.13% FFA);² retention across the chain is therefore a product of two stage ratios measured on different batches, whereas FU-2 uses the carotene measured directly in the final oil.

Table S1: Pilot deodorization electricity per 100 kg batch.

Item	kWh batch ⁻¹	Share (%)
Heater	6.06	64.2
Vacuum pump	2.76	29.2
Cooling-water pump	0.37	3.9
Oil pump	0.25	2.6
Nitrogen production	0.002	<0.1
Total	9.44	100

S2 Process scale and heat source scenarios

The industrial scenario applies the same model with three pilot penalties released: vessel surface area per unit mass falls as $V^{-1/3}$ with the charge raised to 10 t (5–20 t); air in-leakage rises as $V^{0.66}$ (exponent 0.5–0.8) while throughput rises linearly; and oil-to-oil heat recovery of 0.70 (0.50–0.85) is applied, as in refinery deodorizers.³ Temperature, holding time, pressure and carotene retention are unchanged. The scenario gives 36.0 kWh t⁻¹ (129.5 MJ t⁻¹). An independent full-scale deodorizer consumes 131.28 MJ t⁻¹, 127.41 MJ of it thermal;³ it lies inside the 87.6–190.6 MJ t⁻¹ band obtained by varying the three scaling assumptions, so the agreement bounds the scaling rather than fixing its value.

In the steam scenarios the industrial heater duty (19.7 kWh t⁻¹ of electricity at $\eta_{\text{heater}} = 0.95$) is supplied instead as boiler heat, requiring 84.3 MJ t⁻¹ of fuel at an assumed boiler and distribution efficiency of 0.80 (0.70–0.85, not sourced); the remaining 16.3 kWh t⁻¹ stays on the grid. Combustion factors are IPCC 2006 defaults⁴ with AR6 GWP100 (CH₄ 27.0, N₂O 273); biogenic CO₂ from biomass is excluded (Table S2).

Table S2: Deodorization scenarios, kg CO₂-eq per tonne RPO.

Scenario	Fuel factor, kg CO ₂ /CH ₄ /N ₂ O per TJ	kg CO ₂ -eq t ⁻¹
Pilot, electric	—	64.7
Industrial, electric	—	24.5
Industrial, steam from sub-bituminous coal	96 100 / 1 / 1.5	19.2
Industrial, steam from natural gas	56 100 / 1 / 0.1	15.8
Industrial, steam from palm biomass	(100 000 biogenic) / 30 / 4	11.2

S3 Deacidification mass balance, chemicals, water and transport

Mass balance. The caustic dose follows $\text{RCOOH} + \text{NaOH} \rightarrow \text{RCOONa} + \text{H}_2\text{O}$ with FFA as palmitic acid (256.42 g mol⁻¹) at the measured 3.62% and 17.5% excess:² 6.64 kg NaOH per tonne CPO as 60.0 kg of 16 °Bé solution (11.06% w/w from SG = 145/(145 – 16)).⁵ The stage loses 98.4 kg t⁻¹ CPO; 35.0 kg is saponified FFA and 63.4 kg non-FFA loss. Wet soapstock (155.9 kg) comprises 38.0 kg sodium palmitate, the 63.4 kg non-FFA loss, 53.4 kg water carried with the caustic solution and 1.2 kg unreacted NaOH; the wash water is separated after soapstock removal and is not part of it.

Non-FFA loss on a dry basis. The source does not resolve entrained oil from gums and impurities. Using measured moisture (CPO 0.14%, NRPO 0.58%),² CPO carries 1.40 kg water and NRPO 5.23 kg, so the dry-basis loss is 102.2 kg and the non-FFA loss 67.2 kg. The mass-allocation factor moves from 0.9016 to 0.8976 on a dry basis, within the range already evaluated.

Carotene recovery. Carotene entering is 460.13 g t⁻¹ CPO and leaving 419.21 g, a recovery of 91.11% against the 87.30% reported. The reported FFA reduction reproduces within 0.06 percentage points, so the table describes the same run; the gap closes if the 90.16% yield refers to degummed oil, implying a CPO → NRPO yield of 86.39%, which is carried as the lower bound of the deacidification-yield axis.

Energy. Sensible heat of CPO to 80 °C (102.50 MJ t⁻¹), wash water to 67.5 °C (12.54 MJ) and caustic solution to 61 °C (7.77 MJ; heat capacity of water used, an upper bound), divided by 0.95, gives 35.9 kWh t⁻¹ CPO or 39.8 kWh t⁻¹ NRPO.

Chemicals, water, wastewater and transport are listed in Table S3. The NaOH factor re-expresses the 76.13% electricity share of the European chlor-alkali eco-profile (0.66 kg CO₂-eq kg⁻¹ at 0.392 kg CO₂-eq kWh⁻¹) on the Indonesian grid.⁶ Wash-water methane is COD × B₀ × MCF with B₀ = 0.25 kg CH₄ kg⁻¹ COD;⁷ physical refineries report far lower COD (0.088 kg m⁻³),⁸ so the central value is conservative. Summed over the full range of factors and activity data, these items contribute 0.009–0.105 kg CO₂-eq kg⁻¹

RPO. Soapstock acid splitting is outside the boundary; charged in full to RPO it would add 0.002 kg CO₂-eq kg⁻¹.

Table S3: Upstream chemicals, water, wastewater and transport.

Item	Factor (range)	Source	kg CO ₂ -eq t ⁻¹ CPO
NaOH, 6.64 kg	1.03 (0.53–1.15) kg kg ⁻¹	6,9	6.83
H ₃ PO ₄ , 1.275 kg	1.00 (0.45–3.12) kg kg ⁻¹	9,10	1.27
Process water, 0.08 m ³	0.19 (0.19–0.46) kg m ⁻³	11,12	0.015
Wash-water CH ₄	COD 1.35 (0.088–3.0) kg m ⁻³ ; MCF 0.8 (0–0.8)	7,13	0.58
CPO transport	120 (50–300) km × 0.095 (0.0775–0.22) kg t ⁻¹ km ⁻¹	9,11,12,14	11.4

S4 Grid emission factor

The R0 manuscript used 0.89 t CO₂ MWh⁻¹ for the Sumatra grid. The official table shows this is the ex-post combined margin (operating margin 0.73, build margin 1.05) for 2017,¹⁵ a construct for crediting mitigation projects rather than an average supply mix, and it covers CO₂ only. No official average-mix factor is published. The revision uses the 2024 Indonesian life cycle grid intensity, 0.681 kg CO₂-eq kWh⁻¹, which includes upstream fuel supply and all gases.¹⁶ Its range, 0.54–0.77, is a bottom-up estimate for the 2024 Sumatra generation mix¹⁷ with IPCC default combustion factors;⁴ CH₄ and N₂O add 0.4% to combustion CO₂ (Table S4).

Table S4: Candidate grid factors, kg per kWh.

Factor	Value	Use here
Sumatra combined margin 2017, CO ₂ ¹⁵	0.89	R0 value; not an average mix
Sumatra operating margin 2017, CO ₂ ¹⁵	0.73	fossil plants only
Indonesia 2024, life cycle CO ₂ -eq ¹⁶	0.681	reference
Sumatra 2024 mix, bottom-up CO ₂ -eq	0.54–0.77	sensitivity range

S5 Vitamin A conversions

Retinol activity equivalents follow 1 µg RAE = 12 µg dietary β-carotene = 24 µg α-carotene = 1 µg retinol, and 1 IU = 0.300 µg retinol.^{18,19} Retinyl palmitate supplies 0.550 µg per IU.²⁰ RPO at 375.33 mg kg⁻¹ carotene delivers 31.3 mg RAE kg⁻¹ (104 IU g⁻¹) as β-carotene,

or 25.2 with a 38.9% α -carotene share.²¹ Fortification at the national standard of 45 IU g⁻¹²² is 13.5 mg RAE kg⁻¹ and 24.75 mg retinyl palmitate kg⁻¹; residual carotene adds 0.15–1.75 mg RAE kg⁻¹. The Indonesian test method reports carotene as not detected below an absorbance of 0.2.¹⁹ The grid covers four backgrounds, three allocation factors, five deodorization scenarios, three retention values and three residual-carotene values (540 combinations; Table S5).

Table S5: Carotene and vitamin A results, reference case and grid range.

Metric	Reference	Grid
FU-2, RPO, g CO ₂ -eq mg ⁻¹ carotene	15.55	3.16–23.36
FU-2, RBDPO with residual carotene	3407	76–3407
FU-2 ratio RBDPO/RPO	219	13–273
FU-3, RPO, g CO ₂ -eq mg ⁻¹ RAE	187	38–280
FU-3, RBDPO fortified, zero-burden fortificant	462	105–462
FU-3 ratio	2.47	1.47–3.08
FU-3 ratio, 38.9% α -carotene	2.00	—
Fortification for parity, IU g ⁻¹	112	69–140
Break-even fortificant burden	negative	negative throughout

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