



RESEARCH PAPERS

Red Palm Oil versus Conventionally Refined Palm Oil: A Cradle-to-Gate Carbon Footprint on Mass, Carotene and Vitamin A Functional Units

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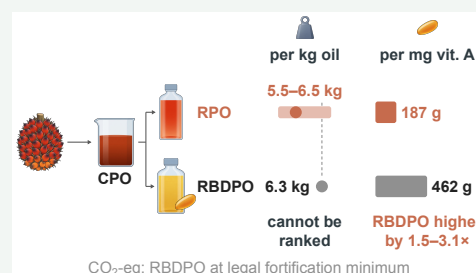
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ABSTRACT

Red palm oil (RPO) retains the provitamin A carotene that conventional refining largely removes, but its life cycle burden has not been quantified. We report an ISO 14067 cradle-to-gate carbon footprint of RPO built from pilot-plant data on Indonesian crude palm oil, with process energy estimated from equipment specifications, and compare it indicatively with refined, bleached and deodorized palm oil (RBDPO) on three functional units: 1 kg of oil, 1 mg of carotene and 1 mg of retinol activity equivalent (RAE). Across the scenario grid the footprint is 1.28–6.47 kg CO₂-eq kg⁻¹, of which 93–99% arises before the refinery; plantation location within Indonesia moves it by 25.4 kg CO₂-eq kg⁻¹ against 0.054 for deodorization scale and heat source. Per kilogram, RPO is 0.46 kg CO₂-eq below RBDPO at the reference case, but the soapstock allocation convention alone reverses the difference, so the oils cannot be ranked. Per milligram of carotene, RBDPO with its residual carotene carries 13–273 times the RPO burden. Per milligram of RAE, RBDPO fortified to the Indonesian minimum carries 1.5–3.1 times the RPO burden even with a burden-free fortificant, and parity would require fortification at 69–140 international units per gram. Only climate change is assessed.



KEYWORDS life cycle assessment; ISO 14067; nutritional functional unit; retinol activity equivalent; food fortification; co-product allocation; Indonesia

1. INTRODUCTION

Indonesia is the largest producer and exporter of refined palm oil [1], and its crude palm oil (CPO) output grew from about 8 to 48 million tonnes between 2001 and 2022 [2]. The greenhouse gas burden of that oil is set largely by land: carbon footprints of Indonesian CPO resolved to district level span 0.7–26.0 kg CO₂-eq kg⁻¹ [3], reflecting forest and peat conversion [4–7] more than mill practice.

Crude palm oil is also one of the richest natural sources of provitamin A carotenoids [8], carrying 476–615 mg kg⁻¹ β-carotene in commercial grades [9]. Conventional refining removes them: the oil is bleached and then deodorized at about 260 °C [9, 10], and carotenoid losses of 93.7% and more are reported [11, 12], and refining strips micronutrients from vegetable oils generally [13, 14]. Red palm oil (RPO) is produced by a route chosen to retain them, which omits bleaching and deodorizes at moderate temperature. On Indonesian CPO the route has been run at pilot scale in two studies, caustic deacidification to neutralized red palm oil (NRPO) [15] and deodorization at 140 °C, which gave a neutralized, deodorized oil retaining 375 mg kg⁻¹ total carotene [16]; the route and its products have been reviewed [17, 18].

The retained carotene has a documented nutritional function. Red palm oil has been trialed as an intervention food [19, 20] and tested against synthetic retinyl palmitate as a delivery vehicle [21], and across nine randomized trials it reduced the risk of vitamin A deficiency (relative risk 0.55) [22]. The deficiency remains widespread, affecting 44% of children in south Asia and 48% in sub-Saharan Africa in 2013 [23]. Indonesia already mandates vitamin A in packaged palm cooking oil, and its current regulation counts provitamin A carotene toward that requirement [24]. In Indonesia, RPO and fortified conventional oil are therefore two routes to the same regulated function.

Whether the shorter RPO route lowers the product footprint is a life cycle question rather than a process one, because both oils draw on the

same cultivation and milling system, which dominates the chain wherever stages have been resolved [25, 26]. Life cycle assessment (LCA) studies of conventionally refined palm oil are numerous [1, 26–28], including an Indonesian-language assessment of palm cooking oil [29], and the wider literature extends to mill waste [30] and biodiesel [31]. Red palm oil, however, is absent from it: searches of Scopus, ScienceDirect, Springer Nature, Crossref, OpenAlex, Google Scholar and the Indonesian Garuda index, in English and Indonesian, returned no life cycle inventory or carbon footprint of RPO.

A second gap concerns the basis of comparison. ISO 14044 requires the functional unit to represent the function delivered [32], yet food LCA mostly compares products by mass, a mismatch raised repeatedly as the field's open methodological question [33, 34]. Nutritional functional units are mostly nutrient-density indices that aggregate many nutrients to rank foods and diets [35–40], and single-attribute units, such as protein quality [41], are rare. RPO and conventionally refined, bleached and deodorized palm oil (RBDPO) are both refined from the same crude oil and differ chiefly in one attribute, which a mass basis conceals and an aggregate index dilutes.

This study reports a cradle-to-gate carbon footprint of RPO under ISO 14067 and asks whether, and on what basis, it can be compared with RBDPO. Three functional units are carried through one inventory: per kilogram of oil, per milligram of carotene, and per milligram of retinol activity equivalent (RAE), the last against RBDPO fortified to the Indonesian minimum. The comparison with RBDPO is indicative. The comparator is taken from published data under a co-product convention that differs from the one applied to RPO, so the comparison does not meet the ISO 14044 conditions for a comparative assertion.

2. MATERIALS AND METHODS

2.1 Goal, Scope and Functional Units

The study is a cradle-to-gate product carbon footprint under ISO 14067 [42], following the inventory requirements of ISO 14044 [32]. It covers a single impact category, climate change, expressed as global warming potential over 100 years (GWP100), and it ends at the refinery gate. Distribution, use and end-of-life are excluded, so carotene losses during domestic heating [43] are not modeled. Throughout, RPO denotes the red palm oil produced by the pilot route, the oil that the source study calls neutralized deodorized palm oil (NDPO) [16], and NRPO denotes the neutralized intermediate.

Three functional units (FU) are carried through the same inventory. FU-1 is 1 kg of oil at the refinery gate, the basis of published palm oil LCA studies. FU-2 is 1 mg of total carotene delivered in the oil at the gate, the attribute for which RPO is produced. FU-3 is 1 mg of retinol activity equivalent (RAE) delivered at the gate, which places carotene and preformed vitamin A on one scale and admits fortified RBDPO as a comparator (Section 2.7).

RPO is compared with RBDPO made from the same CPO, and the comparison is indicative only. The comparator is represented by a published refinery-stage burden that embeds a substitution credit, whereas the RPO route is allocated (Section 2.5). Because the two systems do not use equivalent co-product rules, the study makes no comparative assertion in the sense of ISO 14044.

2.2 System Boundary and Data

The system runs from cultivation to oil at the refinery gate (Fig. 1) and is divided into a background and a foreground. The background covers cultivation, fruit transport and milling, ending with CPO at the mill gate. It is taken from published palm oil inventories (Section 2.6) and is common to both oils. CPO transport from the mill to the refinery is added to both, at 120 km, a Malaysian distance, by articulated truck [27, 44] and 0.095 kg CO₂-eq t⁻¹ km⁻¹ [45], and is varied over 50–300 km and 0.0775–0.22 kg CO₂-eq t⁻¹ km⁻¹ [1, 44].

The foreground comprises degumming, caustic deacidification and moderate-temperature deodorization. It is built here from two pilot-plant studies on Indonesian CPO [15, 16], and these studies are the reason the work is set in Indonesia: they are the only published process data for the RPO route on Indonesian CPO, and the Indonesian background is available at district resolution [3]. Neither source reports energy use, so all foreground energy is estimated.

Every inventory value is labeled *measured* (reported in the source), *estimated* (derived here by a stated calculation) or *assumed* (not reported, with a range). The inventory is summarized in Table 1; derivations are given in Supporting Information Sections S1–S3.

2.3 Foreground Inventory

Degumming and deacidification. CPO is degummed with 85% phosphoric acid at 0.15% of CPO mass and 80 °C, then neutralized with 16 °Bé sodium hydroxide at 17.5% excess and 61 °C, centrifuged and washed with hot water [15]. The caustic dose follows from the measured acidity of the feed, 3.62% free fatty acid (FFA) as palmitic acid. Wash water is not reported and is set at 8% of the CPO entering neutralization (80 kg t⁻¹ CPO), within the 3–10% industrial range [46]. Stage energy is modeled to first order as the sensible heat of the CPO (to 80 °C), the wash water (to 67.5 °C) and the caustic solution (to 61 °C), each from an assumed ambient 30 °C. Agitation, pumping and centrifugation are omitted, so the resulting 39.8 kWh t⁻¹ NRPO is a lower bound, and it is varied up to threefold in the sensitivity analysis.

The stage loses 98.4 kg per tonne of CPO. The FFA balance (3.62% in CPO, 0.13% in NRPO) assigns 35.0 kg of this to saponified FFA, and the remaining 63.4 kg is non-FFA loss: entrained neutral oil together with gums and impurities, which the source does not resolve. On a dry basis, using the measured moisture of CPO (0.14%) and NRPO (0.58%) [15], the non-FFA loss is 67.2 kg, so correcting for the wash water retained in NRPO enlarges rather than reduces it (Section S3).

Deodorization. The pilot unit is a 100 L electrically heated batch deodorizer charged with 100 kg NRPO, heated to 140 °C at 20 mmHg under

nitrogen sparging, held 1 h and cooled under vacuum [16]. Energy is estimated from a heat balance (sensible and latent heat, vessel losses) and from a vacuum pump sized for the non-condensable gas load, as detailed in Section S1. On this basis the pilot case requires 9.44 kWh per batch, or 94.9 kWh t⁻¹ RPO.

Scale and heat source. Batch figures from a pilot unit would burden RPO with a scale artifact when it is set against an industrial comparator, so three scenario families are carried. The *pilot* scenario applies the model at the measured pilot conditions. The *industrial* scenario removes three pilot penalties through stated scaling laws (Section S2) and gives 36.0 kWh t⁻¹, consistent with an independent full-scale benchmark [47]. Industrial deodorizers are heated by steam or thermal oil rather than electrically, so the *industrial steam* scenarios replace the heater duty of the industrial case with boiler heat fired by sub-bituminous coal, natural gas or palm biomass. These scenarios use an assumed boiler efficiency of 0.80 and the default combustion factors of the Intergovernmental Panel on Climate Change (IPCC) [48], while vacuum, pumps and nitrogen remain electric. Biogenic CO₂ from biomass is excluded, and its CH₄ and N₂O are counted.

Chemicals, water and wastewater. Upstream burdens are included for NaOH (1.03 kg CO₂-eq kg⁻¹, the chlor-alkali eco-profile [49] with its electricity share re-expressed on the Indonesian grid), phosphoric acid (1.00 kg CO₂-eq kg⁻¹, an Indonesian wet-process plant [50]) and process water [45]. Methane from wash-water treatment follows the IPCC method [51], with a chemical oxygen demand (COD) of 1.35 kg m⁻³ measured in palm refinery effluent [52]. Because the treatment is not reported, a deep anaerobic lagoon (methane correction factor 0.8), the most emissive option, is assumed. Together these inputs add 9.7 kg CO₂-eq t⁻¹ NRPO (Table S3).

2.4 Impact Assessment

Impacts are characterized as GWP100 with IPCC AR6 factors [53], using the non-fossil methane factor for combustion methane. Electricity is characterized with the Indonesian grid average of 0.681 kg CO₂-eq kWh⁻¹ for 2024, a life cycle value including upstream fuel supply [54], varied in the sensitivity analysis of the deodorization energy model over 0.54–0.77, a bottom-up estimate for the 2024 Sumatra generation mix that uses direct combustion factors and omits upstream fuel supply [55]. Official Indonesian grid factors are CO₂-only operating, build and combined margins intended for crediting mitigation projects [56]; they include no CH₄ or N₂O and are not average-mix factors, so they are not used here (Section S4).

Land use change (LUC) enters the background in its direct form, amortized over 20 years following PAS 2050 [57], the PalmGHG calculator [58] and the attributional background source [26]. Indirect LUC is excluded as a consequential construct [59]. Biogenic CO₂ exchange in the crop cycle is also excluded, whereas methane from mill effluent is included.

2.5 Allocation

Multifunctionality is common in agricultural systems, and the way it is handled can change the results of food LCA [60, 61]. In this system the choice arises at deacidification, which yields NRPO together with 155.9 kg t⁻¹ CPO of wet soapstock, a saleable stream. Allocation at this stage partitions both the upstream burden carried by the CPO and the burden of the stage itself, so three treatments are evaluated. The first treats soapstock as waste and assigns the whole burden to NRPO (factor 1.0). The second allocates by CPO-derived mass, 901.6 : 98.4 (0.9016), excluding the water and sodium added at the stage. The third allocates by the mass of wet soapstock (0.8525). The first two define the FU-1 result range, and the third bounds the sensitivity analysis. Economic allocation over a soapstock-to-oil price ratio of 0.15–0.60 falls within the same range. Acid splitting of soapstock is performed by its buyer and lies outside the boundary.

The RBDPO comparator handles its own co-product differently. Its published refinery stage embeds a substitution credit for palm fatty acid distillate [62]. Substitution and allocation are alternative answers to the same multifunctionality problem and need not agree [63], and this is the non-equivalence noted in Section 2.1.

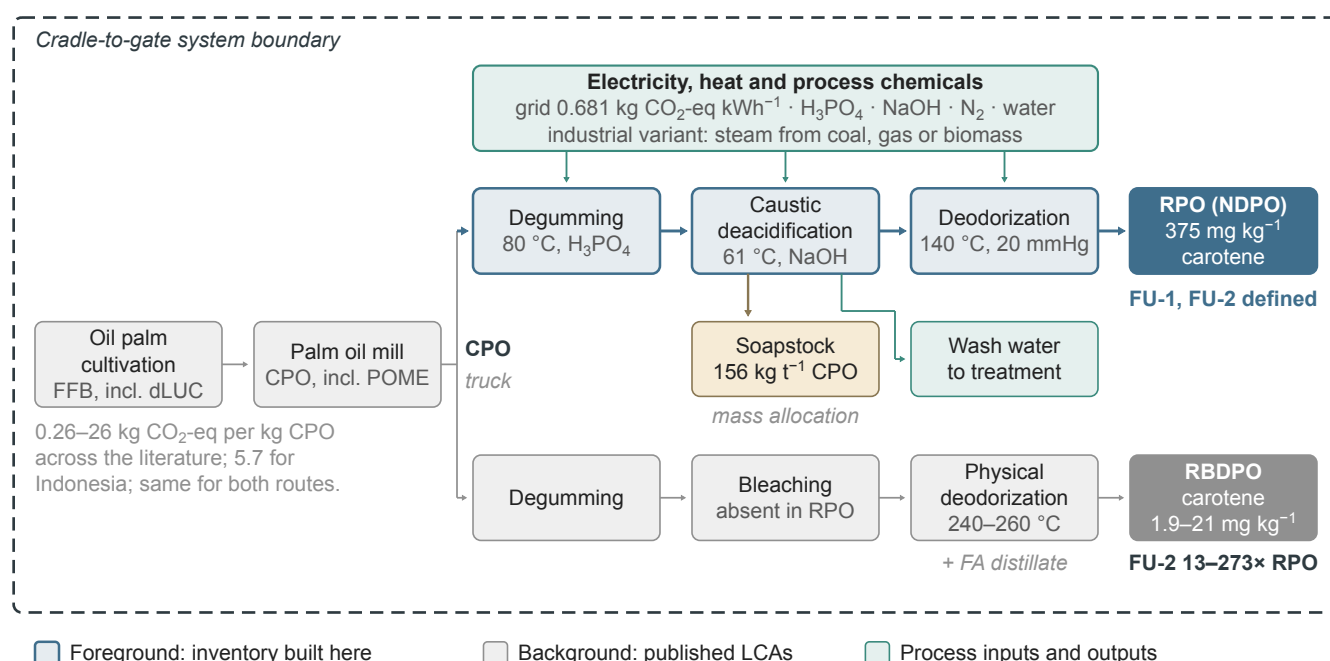


Figure 1. System boundary. Both routes start from the same CPO; RPO is refined chemically and deodorized at 140 °C, RBDPO physically at 240–260 °C. FFB, fresh fruit bunches; dLUC, direct land use change; POME, palm oil mill effluent.

Table 1. Foreground inventory of the RPO route. FFA, free fatty acid.

Flow	Value	Unit	Status	Basis
<i>Degumming and deacidification, per t CPO</i>				
Phosphoric acid, 100% (as 85% solution)	1.275 (1.50)	kg	measured	0.15% of CPO [15]
Sodium hydroxide, 100% (as 16 °Bé)	6.64 (60.0)	kg	estimated	stoichiometry, 17.5% excess
Wash water	80	kg	assumed	8% of CPO mass [46]
Electricity (thermal duty)	39.8	kWh t ⁻¹ NRPO	estimated	lower bound
Chemicals, water, wash-water CH ₄	9.7	kg CO ₂ -eq t ⁻¹ NRPO	estimated	Table S3
NRPO	901.6	kg	measured	90.16% yield [15]
Wet soapstock	155.9	kg	estimated	mass balance
non-FFA loss (oil, gums, impurities)	63.4	kg	estimated	loss minus FFA
sodium soap	38.0	kg	estimated	stoichiometry
water with caustic	53.4	kg	estimated	16 °Bé solution
unreacted NaOH	1.2	kg	estimated	17.5% excess
<i>Deodorization, per t RPO</i>				
Electricity, pilot	94.9	kWh t ⁻¹	estimated	Section S1
Electricity, industrial	36.0	kWh t ⁻¹	estimated	scaled, Section S2
Stage yield	0.995	kg kg ⁻¹	estimated	water, distillate
Carotene in RPO	375.33	mg kg ⁻¹	measured	[16]

2.6 Background System

No commercial database was used. Instead, four background scenarios span the published cradle-to-mill-gate burden of CPO (Table 2), from a single best-performing company through the industry averages for plantations certified and not certified by the Roundtable on Sustainable Palm Oil (RSPO) to the Indonesian average. Three of these scenarios, drawn from two sources, report their burden per kg of refined oil. These burdens are converted to a CPO basis by subtracting the published refinery stage, 0.31 kg CO₂-eq kg⁻¹, and applying the refinery yield of each source, 0.926 for United Plantations and 0.953 for the industry averages [26, 62]. The Indonesian average and the consequential bound report per kg CPO and are used directly [2, 3]. The Indonesian district-level inventory [3] provides the reference case and the spatial bounds. The consequential value without land use change [2] serves as a bound on the literature rather than as a result scenario. The RBDPO comparator is built from the burden of the same CPO divided by the refinery yield of 0.953, plus the published refinery stage, which already contains its chemicals, water and energy [62].

2.7 Vitamin A Basis and Fortified Comparator

For FU-2 the comparator is RBDPO with its residual carotene, which is small but measurable: 1.85 mg kg⁻¹ after standard refining [64], and 3.24–21.02 mg kg⁻¹ on one refined sample measured by two instruments under ISO 17932 [65]. The trading specification for refined palm oil regulates acidity, moisture, iodine value, melting point and color, not carotene [66].

For FU-3, carotene is converted at 12 µg β-carotene per µg RAE and preformed vitamin A at 0.300 µg retinol per international unit (IU), the conventions of both the Indonesian regulation [24] and the dietary reference intakes [67]. Treating all carotene as β-carotene favors RPO, so a 38.9% α-carotene share [68] converted at 24:1 is tested separately. The comparator is RBDPO fortified with retinyl palmitate to the Indonesian minimum of 45 IU g⁻¹ [69], 13.5 mg RAE kg⁻¹ or 24.75 mg retinyl palmitate per kg oil [70]. No published carbon footprint of synthetic vitamin A was found, so its burden is set to zero, the bound most favorable to the comparator. Two break-even quantities are reported instead: the fortificant burden and the fortification level at which fortified RBDPO would equal RPO per mg RAE.

Table 2. Cradle-to-mill-gate burden of CPO used as background.

Source system	kg CO ₂ -eq kg ⁻¹ CPO	Basis	Ref.
Consequential, no land use change	0.26	no LUC, by-product substitution; bound only	[2]
Indonesia, lowest district (Hulu Sungai Tengah)	0.7	spatially explicit; bound only	[3]
United Plantations 2024 (best performer)	1.21	single company; excl. indirect LUC and conservation offset	[62]
RSPO-certified average, Indonesia + Malaysia	2.96	industry average, 2016	[26]
Non-certified average, Indonesia + Malaysia	4.78	industry average, 2016	[26]
Indonesia average, outside Java	5.7	spatially explicit, reference case	[3]
Indonesia, highest district (Pontianak)	26.0	spatially explicit; bound only	[3]

2.8 Calculation and Sensitivity Analysis

The inventory is computed by six chained Python scripts. Every parameter carries a value, unit, status, source and range, and each script reads the outputs of its predecessors rather than restating their numbers. Result ranges are the minimum and maximum over the scenario grid. For FU-1 this grid combines the four background scenarios, the five deodorization scenarios and the first two allocation treatments. For FU-2 and FU-3 it comprises all 540 combinations of the four backgrounds, three allocation treatments, five deodorization scenarios, three carotene retentions and three residual carotene levels in RBDPO. At system level, nine axes are varied one at a time from the reference case (Indonesian average background, pilot deodorization, mass allocation): background source; plantation location within Indonesia; allocation basis; deacidification yield; CPO transport; deodorization scale and heat source; deacidification energy; the refinery-stage figure subtracted in background conversion; and carotene retention (51.5–71.1%, as measured at 130–150 °C and 1–2 h [16], against 69.8% at the reference case, with the carotene content of RPO scaled in proportion). The refinery-stage axis moves only the scenarios converted from refined oil, so it leaves the reference case unchanged. The RPO–RBDPO difference is analyzed over the same axes.

3. RESULTS AND DISCUSSION

3.1 Refining Inventory and Stage Burdens

Table 1 and Fig. 2 trace the refining chain from 1 kg of CPO to 0.897 kg of RPO. The finished oil still carries 375.33 ± 22.87 mg kg⁻¹ of total carotene, the property that sets it apart from conventionally refined palm oil.

Of the two refining stages, deodorization is the one whose burden depends most on how the plant is run. In the pilot scenario it emits 64.7 kg CO₂-eq t⁻¹ RPO. Scaling the same process to an electrically heated industrial deodorizer lowers this to 24.5, and replacing the electric heater with boiler steam lowers it further, to 19.2, 15.8 and 11.2 kg CO₂-eq t⁻¹ for coal, natural gas and biomass firing. Steam heating comes out lower because boiler heat avoids the conversion losses embedded in grid electricity.

Degumming and deacidification together emit 36.8 kg CO₂-eq t⁻¹ NRPO. Thermal energy accounts for 27.1 of this, and chemicals, process water and methane from the wash water for the remaining 9.7. Among the chemical inputs NaOH supply is the largest, at 6.8 kg CO₂-eq t⁻¹ CPO (Table S3). Transporting CPO from the mill to the refinery adds 0.011 kg CO₂-eq kg⁻¹ CPO, a term shared by both products because both start from the same oil.

3.2 Carbon Footprint per Kilogram of Oil

At the reference case (Indonesian average background, pilot deodorization and mass allocation), the footprint of RPO is 5.84 kg CO₂-eq kg⁻¹. Almost all of it arrives with the CPO. Cultivation, milling and transport contribute 5.740 kg CO₂-eq kg⁻¹ (98.3%), whereas deacidification adds 0.033 (0.6%) and deodorization 0.065 (1.1%). Varying the background, the deodorization scenario and the allocation treatment widens the result to 1.28–6.47 kg CO₂-eq kg⁻¹ (Table 3), and across this scenario grid the foreground built here accounts for 0.8–7.4% of the total. The spatial bounds show how much further the background can move the result: with the lowest- and highest-emitting Indonesian districts as background, the footprint runs from 0.76 to 29.10 kg CO₂-eq kg⁻¹ over the same deodorization and allocation scenarios.

Comparison with published footprints is limited in two ways. No life cycle inventory of RPO exists, so the foreground cannot be checked against an independent one. Placement against refined palm oil is also less independent than it appears, because three of the background scenarios were themselves derived from those publications. What can be compared is the structure of the result, and on that the agreement is clear: the stage-resolved assessments available place most of the burden upstream of the refinery [25, 28, 71]. Minimal-refining routes for carotene-bearing palm fractions, such as oil from palm-pressed fiber, are being developed without such data [72].

The absolute values are consistent with the literature as far as the literature allows. A recent footprint of Indonesian refined palm oil, 2.20 kg CO₂-eq kg⁻¹ [1], falls within the range reported here. The RPO footprint on the Indonesian reference background, 5.78–6.47 kg CO₂-eq kg⁻¹, lies above the 3.42 and 5.32 kg CO₂-eq kg⁻¹ reported for RSPO-certified and non-certified refined oil averaged over Indonesia and Malaysia [26]. The two estimates differ in reference year, boundary detail and producer population, and the published data do not allow the difference to be assigned to any one of these.

3.3 Sensitivity and Where a Lower Footprint Would Come From

Fig. 3 ranks the sensitivity axes by how far each moves the footprint. Plantation location within Indonesia dominates: it moves FU-1 by 25.43 kg CO₂-eq kg⁻¹, more than five times the next axis, the choice of background source (4.51). An accounting choice and a data-reading choice follow, the allocation basis at 0.94 and the deacidification yield at 0.25. The refinery parameters come last. CPO transport moves FU-1 by 0.062, deodorization scale and heat source by 0.054 and the deacidification energy model by 0.049, each 400 to 500 times smaller than the plantation-location swing. The refinery-stage axis leaves both units unchanged at the reference case, whose background needs no conversion. Carotene retention is the only axis that leaves FU-1 unchanged but moves FU-2, by 5.81 g CO₂-eq mg⁻¹, because it alters only the carotene content of the oil.

This ranking means that where the CPO is grown outweighs every refinery parameter by two to three orders of magnitude, because 93–99% of the footprint is fixed before the oil reaches the refinery. For a producer seeking a lower-carbon RPO, the leverage therefore lies in sourcing rather than in refinery design. That leverage is plausible in practice: expansion that avoids forest and peat is compatible with continued growth in Indonesian output [73], and certification has reduced deforestation on certified plantations [74].

3.4 Per-Kilogram Difference from RBDPO

At the reference case RBDPO comes to 6.30 kg CO₂-eq kg⁻¹ against 5.84 for RPO, a difference (RPO minus RBDPO) of -0.46 kg CO₂-eq kg⁻¹, or 8.0% of the RPO footprint. Taken alone, this figure would favor RPO, but it does not survive the sensitivity analysis (Fig. 4). One axis reverses its sign, and it is an accounting choice rather than a physical parameter: with soapstock treated as waste the difference becomes +0.17, and with mass allocation on wet soapstock it widens to -0.78 . Across these allocation bases the RPO footprint moves from 5.52 to 6.47 kg CO₂-eq kg⁻¹, while RBDPO stays at 6.30. Plantation location, the largest axis for the footprint itself, moves the difference from -0.24 to -1.36 but never brings it to zero.

The reason lies in how much CPO each product draws. One kilogram of RPO requires 1.115 kg of CPO. With soapstock treated as waste it carries the burden of all 1.115 kg, whereas under mass allocation it

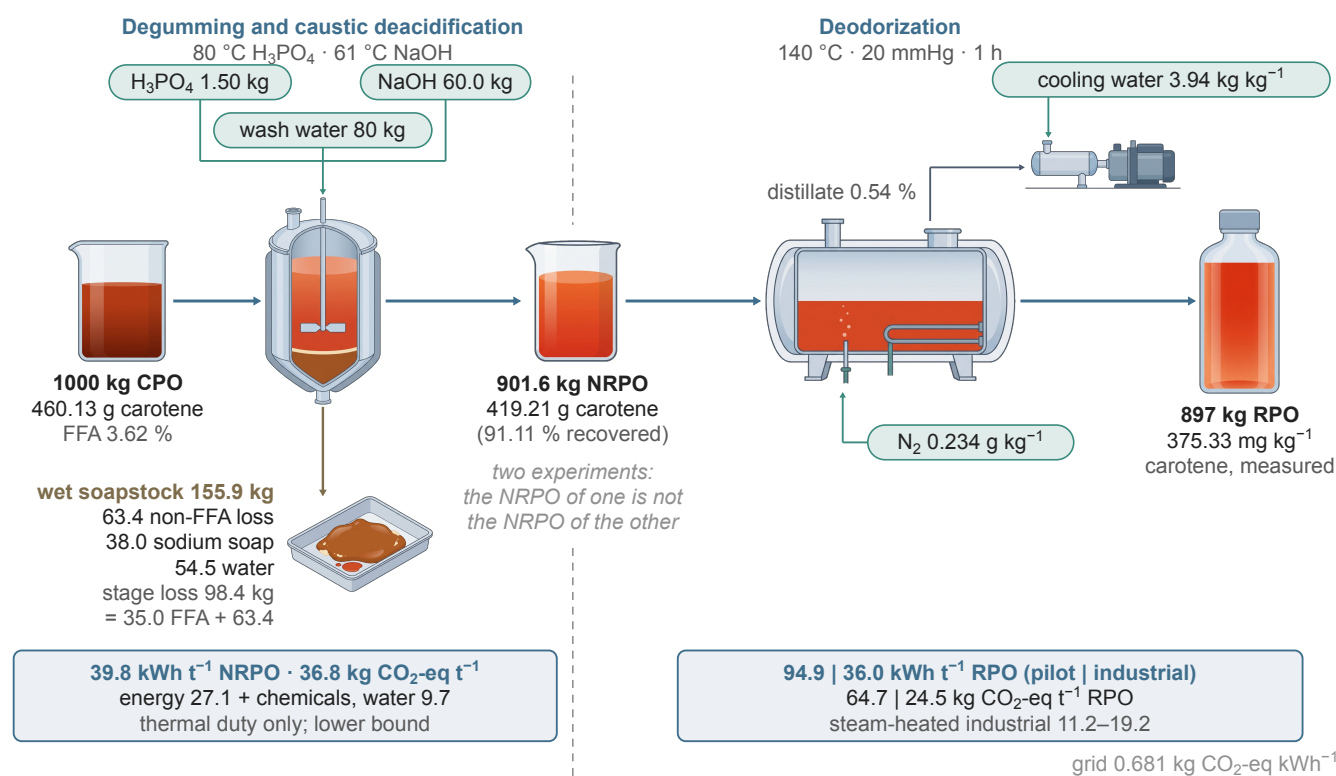


Figure 2. Foreground refining chain with inventory per tonne of CPO (deacidification) and per tonne of RPO (deodorization). Green, process inputs; brown, soapstock; boxes, stage electricity and carbon footprint; dashed line, seam between the two source experiments. Pictorial elements generated with Google Gemini.

Table 3. Cradle-to-gate footprint of RPO by background system (ranges over deodorization scenarios and allocation treatments).

Background system	FU-1 (kg CO ₂ -eq kg ⁻¹)	FU-2 (g CO ₂ -eq mg ⁻¹ carotene)	Role
United Plantations 2024	1.28–1.47	3.40–3.91	result
RSPO-certified average	3.03–3.42	8.09–9.11	result
Non-certified average	4.85–5.44	12.93–14.48	result
Indonesia average, outside Java	5.78–6.47	15.41–17.23	reference
Consequential, no land use change	0.32–0.40	0.85–1.08	lower bound
Indonesia, lowest district	0.76–0.89	2.02–2.38	spatial bound
Indonesia, highest district	26.19–29.10	69.77–77.52	spatial bound

is charged with the burden of 1.005 kg, against 1.049 kg for RBDPO. The burden per kilogram of CPO is identical for the two oils, so only the shared part of that burden cancels in the difference. The remainder scales with the background, which varies 37-fold across districts. The mass balance alone suggests a yield penalty for the caustic route, but that penalty appears only when soapstock is treated as waste. It is therefore an artifact of the allocation convention rather than a property of the route.

Three features of the comparison prevent the reference difference from being read as a ranking. First, its sign depends on a co-product convention, not on an uncertainty in the system itself. Convention choices have reordered food comparisons before [75], and they do so here: the convention alone reverses the sign of the result. Second, the two systems are not treated alike: RPO is allocated, whereas the comparator carries an embedded substitution credit, so the comparison does not meet the equivalence that ISO 14044 requires of a comparative assertion. Third, the convention alone moves the difference by 0.94 kg CO₂-eq kg⁻¹, nearly as much as the 1.12 by which plantation location moves it across districts, so a methodological choice weighs about as much as the largest physical axis. On a mass basis, therefore, the two oils cannot be ranked.

3.5 Carotene and Vitamin A Functional Units

The comparison changes once the functional unit reflects what RPO is produced for. On FU-2 the RPO reference case is 15.55 g CO₂-eq mg⁻¹

carotene. It spans 3.40–17.23 across the four result backgrounds of Table 3, and 3.16–23.36 when carotene retention and the wet-soapstock bound are also varied (Table 4). RBDPO is not carotene-free. With its measured residual carotene of 1.85 mg kg⁻¹ the comparator is defined on FU-2, but its value is large: 3407 g CO₂-eq mg⁻¹ at the reference case, and 76–3407 over the residual range and the full scenario grid, 13–273 times the RPO value (Table 4; Fig. 5). This ratio is governed almost entirely by the residual carotene, a quantity that conventional refining is designed to drive toward zero. FU-2 therefore shows less about the carbon efficiency of RBDPO than about the fact that it delivers carotene only incidentally.

FU-3 compares the two oils on the function that Indonesian regulation actually sets for cooking oil, vitamin A activity, to which carotene and preformed vitamin A both contribute [24]. RPO delivers 31.3 mg RAE kg⁻¹ at a conversion of 12:1, and RBDPO fortified to the national minimum delivers 13.7. Per mg RAE, the fortified comparator carries 2.47 times the burden of RPO at the reference case and 1.47–3.08 times across the scenario grid, even though its fortificant is assigned no burden at all. Because the comparator already carries the larger burden with a burden-free fortificant, no positive fortificant footprint can close the gap at the national minimum, and the break-even fortificant burden is negative at every point of the grid. Parity would instead require fortifying RBDPO at 69–140 IU g⁻¹, 2.5 times the minimum at the reference case. The result does not depend on treating all carotene as β -carotene: count-

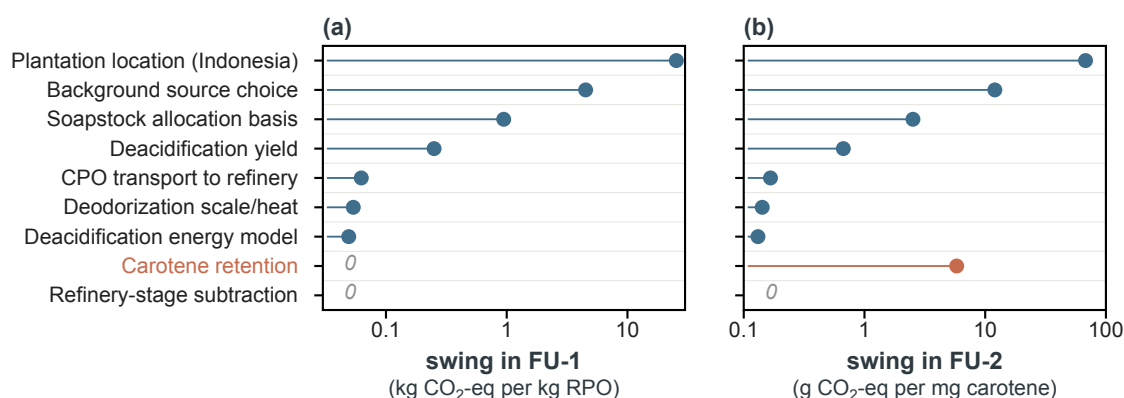


Figure 3. One-at-a-time sensitivity of the footprint on (a) FU-1 and (b) FU-2, ranked by the FU-1 swing; logarithmic axes. Zeros mark axes that leave a unit unchanged.

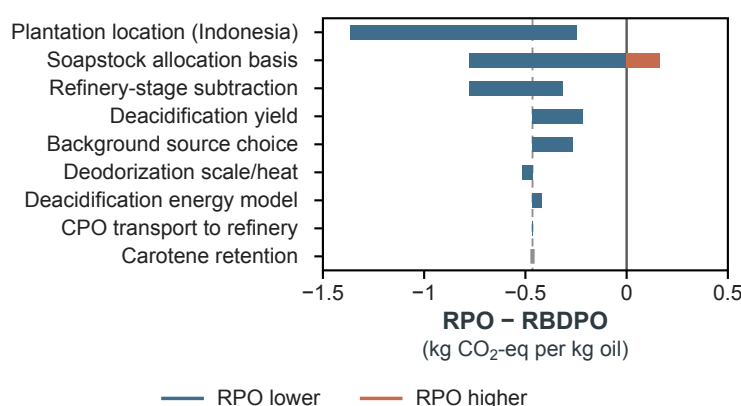


Figure 4. RPO minus RBDPO footprint over the sensitivity axes. Solid line, zero; dashed line, reference case ($-0.46 \text{ kg CO}_2\text{-eq kg}^{-1}$).

Table 4. RPO and RBDPO on the three functional units, reference case with range in parentheses. FU-1 ranges span the result scenarios; FU-2 and FU-3 ranges span all 540 combinations of the scenario grid.

Functional unit	RPO	RBDPO	RBDPO / RPO
FU-1, $\text{kg CO}_2\text{-eq kg}^{-1}$ oil	5.84 (1.28–6.47)	6.30 (reference)	indeterminate; sign of the difference depends on allocation
FU-2, $\text{g CO}_2\text{-eq mg}^{-1}$ carotene	15.55 (3.16–23.36)	3407 (76–3407), residual carotene	219 (13–273)
FU-3, $\text{g CO}_2\text{-eq mg}^{-1}$ RAE	187 (38–280)	462 (105–462), fortified, fortificant burden zero	2.47 (1.47–3.08)
Fortification level for parity, IU g^{-1}	—	112 (69–140)	2.5× national minimum

ing 38.9% of it as α -carotene at 24:1 lowers the reference ratio to 2.00 and the parity level to 90 IU g^{-1} , but leaves the direction unchanged.

The oil also supplies fat, and a multifunctional unit that recognizes this would not change the comparison. Both oils deliver the same fat per kilogram, so any partition of the burden between fat and vitamin A that is applied equally to both scales their FU-3 values by the same factor and leaves the ratio unchanged. The fat function is, in effect, the per-kilogram comparison of Section 3.4, which is indeterminate. The mass basis and the vitamin A basis therefore answer different questions, and only the second separates the two oils.

Two limits apply to this result. FU-3 measures vitamin A activity delivered at the refinery gate, not the amount absorbed. The 12:1 factor for dietary carotene is conservative for carotene dissolved in oil [67], so it is more likely to understate than to overstate the vitamin A value of RPO, while losses during storage and frying, of either carotene or retinyl palmitate, fall outside the boundary. The result also rests on fortification at the regulatory minimum, and oil fortified well above it would narrow the gap or bring the ratio below 1. Measured levels suggest that oil is

commonly fortified near or below the minimum. In a national program evaluation, fortified oil left the factory at 43.6 IU g^{-1} [69], and 32% of regulatory samples taken in 2021–2023 fell below 45 IU g^{-1} [76]; both levels lie below the parity range.

3.6 Limitations

The least certain input in this study is foreground energy, which is estimated from equipment specifications rather than measured, although Section 3.3 shows its effect on the result to be small. The pilot vessel is specified at 100 L but was charged with about 112 L of oil, so heat loss is likely to be understated. The foreground is also pilot-scale, and the industrial scenarios rest on scaling laws, an assumed boiler efficiency of 0.80 and a Malaysian transport distance.

The inventory itself joins two experiments. Their intermediate NRPO differ in carotene by a factor of 1.15, so carotene retention across the chain is the product of two stage ratios rather than a single measurement. The comparator, in contrast, is a published refinery stage rather than an inventory built here, and it follows a different co-product convention. Reference years are not aligned either: the backgrounds refer

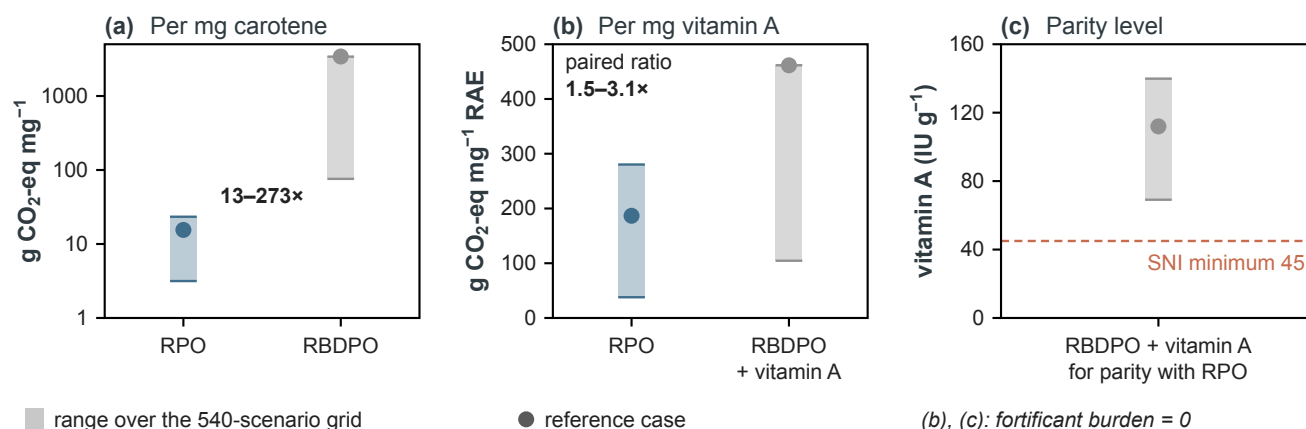


Figure 5. RPO and RBDPO on (a) FU-2, per mg carotene, and (b) FU-3, per mg RAE, with RBDPO fortified to the national minimum; (c) fortification level giving parity with RPO. Fortificant burden set to zero. Bands, full scenario grid; dots, reference case.

to 2015–2024, the process data to 2012–2016 and the electricity factor to 2024. For the vitamin A comparison, the residual carotene of RBDPO rests on two sources, and no footprint of synthetic vitamin A was available. Finally, only climate change is assessed, and other impact categories, eutrophication from mill effluent and fertilizer among them, are not addressed.

4. CONCLUSIONS

This study built a cradle-to-gate carbon footprint of RPO from pilot-plant data on Indonesian CPO and compared it indicatively with RBDPO on three functional units. Across the scenario grid the footprint is 1.28–6.47 kg CO₂-eq kg⁻¹, of which 93–99% arises before the refinery, and plantation location within Indonesia moves it by 25.4 kg CO₂-eq kg⁻¹ against 0.054 for the deodorization scale and heat source. Per kilogram, the comparison with RBDPO cannot be settled, because the sign of the difference is set by the soapstock allocation convention. On vitamin A activity, the function that Indonesian regulation sets for cooking oil, the outcome is clear: per milligram of RAE, RBDPO fortified to the Indonesian minimum carries 1.5–3.1 times the burden of RPO even with a burden-free fortificant. The functional unit, not the refining inventory, therefore decides whether the two oils can be compared and which comes out lower. For a producer of RPO, the lever on the footprint is the sourcing of CPO rather than the design of the refinery. The two extensions most needed are measured process energy, the least certain input, and additional impact categories, eutrophication first.

SUPPLEMENTARY MATERIAL

Supporting Information: Deodorization energy model and vacuum sizing; process scale and heat source scenarios; deacidification mass balance, chemicals, water and transport inventory; grid emission factor basis; vitamin A conversions (PDF).

DECLARATION OF AI-ASSISTED TECHNOLOGIES

Generative AI tools were used to create pictorial elements of Fig. 2 (Google Gemini) and of the graphical abstract (Google Gemini; OpenAI image generation via Codex) and to assist with code and language editing (Claude, Anthropic). The authors reviewed all output and take full responsibility for the content.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Ahmad Nur Sidiq: Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Devi Ardila:** Investigation, Data curation, Writing – original draft. **Chesy Sripratiwi:** Investigation, Data curation, Validation. **Yuni Erlinda:** Formal analysis, Visualization, Writing – review & editing. **Jafar Arifin:** Methodology, Formal analysis, Writing – review & editing. **Muhammad Naufan Rizqullah:** Investigation, Resources, Writing – review & editing.

DECLARATION OF COMPETING INTEREST

The authors declare no competing interests.

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DATA AVAILABILITY

The data and calculation scripts supporting the findings of this study are available from the corresponding author upon reasonable request.

ABBREVIATIONS

COD, chemical oxygen demand; CPO, crude palm oil; dLUC, direct land use change; FFA, free fatty acid; FFB, fresh fruit bunches; FU, functional unit; GWP100, global warming potential over 100 years; IPCC, Intergovernmental Panel on Climate Change; IU, international unit; LCA, life cycle assessment; LUC, land use change; NDPO, neutralized deodorized palm oil; NRPO, neutralized red palm oil; POME, palm oil mill effluent; RAE, retinol activity equivalent; RBDPO, refined, bleached and deodorized palm oil; RPO, red palm oil; RSPO, Roundtable on Sustainable Palm Oil.

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