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Expansion-Share Threshold for Indonesia's B50 Palm Biodiesel

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ABSTRACT

Indonesia raised its mandatory biodiesel blend to B40 in January 2025 and has outlined a pathway toward B50, primarily to strengthen energy security, reduce diesel- import dependence, and absorb domestic crude palm oil. Higher blending, however, increases demand for palm-based fatty acid methyl ester (FAME), making the climate value of B50 dependent on how the marginal feedstock is sourced. This study evaluates the B40-to-B50 switch using a scenario-based operational fuel-cycle screen based on published lifecycle emission factors. The two blends are compared on an equal-energy basis, with land-use change (LUC) treated as a forward-looking sensitivity on incremental feedstock. Coal-mine overburden is used purely as an arbitrary arithmetic placeholder to express volume displacement per bank cubic metre (bcm); the break-even is scale-invariant and independent of this proxy. B50 displaces 0.0335 L of fossil diesel per bcm, independent of LUC assumptions, allocation rules, and emission-factor choices. Under low-LUC sourcing, B50 reduces fuel-cycle greenhouse-gas intensity by 2.8% to 5.6%, depending on engine efficiency penalties; the central estimate is 5.6% under idealised conditions. This benefit is bounded by marginal-feedstock LUC intensity: the break-even is about 44 g CO_2e MJ^{-1} under marginal allocation and 9 g CO_2e MJ^{-1} under precautionary full attribution. Measured mineral-soil forest conversion at 156 g CO_2e MJ^{-1} exceeds both thresholds. Expressed as a sourcing condition, the caps are 28% (marginal) and 6% (full attribution). Crucially, when the European Commission's provisional indirect LUC value for oil crops (55 g CO_2e MJ^{-1}) is included, the marginal threshold (44 g) is exceeded before any direct conversion is counted, implying that under comprehensive accounting the climate case for B50 is likely negative unless indirect effects are explicitly excluded. Because the national B40-to-B50 step requires about 4.06 Mt yr^{-1} of additional CPO, low-LUC supply cannot be assumed by default. Fossil-diesel displacement is therefore robust, whereas the greenhouse-gas benefit is constrained by the expansion share of marginal feedstock, not by any claim that mining itself becomes low-carbon. The study's contribution is the expansion-share limit: a theoretical benchmark against which future empirical estimates of Indonesian expansion share can be compared. It does not provide a measurement protocol or claim that current supply meets this threshold.

Keywords: Carbon intensity, Deforestation, Fossil-diesel displacement, Greenhouse-gas intensity, Indirect land-use change

INTRODUCTION

Indonesia raised its mandatory biodiesel blend from B35 to B40 in January 2025 and announced a pathway toward B50, later deferred in 2026 pending further fuel trials in heavy equipment, rail, and industrial machinery (ESDM 2025; Petromindo 2026; Reuters 2026). The mandate is framed primarily around energy security, diesel-import substitution, foreign-exchange savings, and domestic crude palm oil (CPO) absorption. It is financed through the palm-oil export levy. Domestic instruments such as the Nationally

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Determined Contribution (NDC) and the mandatory Indonesian Sustainable Palm Oil (ISPO) certification do address production-side and land-use emissions, largely in response to broader stakeholder concerns over deforestation, but the mandate itself is not governed by a fuel-carbon-intensity standard comparable to the European Union Renewable Energy Directive (EU 2018). The relevant climate question is therefore not whether B50 satisfies a domestic carbon score, but how much land-conversion emission the switch can tolerate before its fuel-cycle climate rationale is lost.

Each increase in the blend ratio raises demand for palm-based fatty acid methyl ester (FAME), and therefore for palm feedstock. The climate value of this incremental volume is not automatic. It depends on whether the marginal supply is drawn from existing planted areas, replanting, and yield gains, or from new conversion of forest or peatland. These pathways vary by producer: smallholder expansion often differs from that of large plantations, with informal, fire-based clearing near forest margins concentrated among smallholders. This heterogeneity is itself a central challenge for monitoring the expansion share. Measured and modelled studies show that land-use-change (LUC) emissions can dominate the GHG balance of palm biodiesel and can reverse its apparent advantage over fossil diesel once forest or peat conversion is included (Searchinger *et al.* 2008; Harsono *et al.* 2012; Meijide *et al.* 2020). Identifying the point at which this reversal occurs is the central analytical concern of this paper.

The feedstock question is also a food–energy allocation question. The CPO stream that supplies biodiesel is the same stream used for domestic cooking oil. During the 2022 cooking-oil crisis, rising CPO prices, constrained domestic supply, and competing uses were among the leading causes of sharp retail-price increases and state intervention through domestic-market obligations, domestic-price obligations, and a temporary export ban (Fulcrum 2022; Chain Reaction Research 2022). This episode matters because it shows the CPO stream is already supply-constrained and contested between food and fuel, so incremental biodiesel demand cannot be assumed land-neutral. Additional FAME demand must be met through some combination of yield improvement, reallocation from food or export markets, and new planted area. Of these, yield improvement is the clearest low-LUC route, though it is not emission-free due to fertiliser-related N_2O and mechanisation; reallocation from food or export markets is not automatically low-LUC, since displaced supply may be met elsewhere, and new planted area carries the highest LUC risk.

Policy discussion of B50 has largely centred on blend volume, energy security, subsidy cost, and feedstock adequacy. Existing palm-biodiesel LCA studies already imply a simple carbon-intensity break-even between fossil diesel and palm biodiesel. What is rarely developed is the next step: translating that break-even into a theoretical sourcing condition namely the maximum share of incremental feedstock that can come from new high-carbon conversion before the climate benefit disappears. This threshold matters because it connects a fuel-cycle calculation with the practical sourcing problem created by food–energy competition.

This paper quantifies the B40-to-B50 switch through four linked results: (i) LUC-independent fossil-diesel displacement; (ii) fuel-cycle GHG reduction under low-LUC sourcing; (iii) the LUC break-even under marginal and full-attribution allocation rules (the average rule is algebraically equivalent to the marginal rule); and (iv) the expansion-share limit that converts the break-even into a policy-relevant sourcing condition, supported by a national feedstock balance. Coal mining is one of the largest off-road consumers of blended diesel in Indonesia, which makes it a natural setting for testing the fuel-switching claim. The results are expressed per bcm as a scale-independent proxy for diesel-intensive equipment; the break-even threshold itself does not depend on this proxy. Coal-mine overburden is used only as a diesel-

intensive operational stress test to express the physical fuel-switching effect per bank cubic metre (bcm) against externally auditable activity data.

MATERIALS AND METHODS

Study design and system boundary

The study uses a scenario-based fuel-cycle screen to compare the greenhouse-gas (GHG) intensity of the B40 baseline and a B50 scenario. The assessment follows the main scoping elements of ISO 14040/14044, including goal and scope definition, an energy-based functional unit of 1 MJ of fuel delivered, system boundary, and interpretation, but it is not presented as a full third-party-reviewed life-cycle assessment. Primary inventories for cultivation, milling, transesterification, and logistics were not collected. Instead, the model applies published life-cycle emission factors to a clearly defined fuel-switching question. The contribution is therefore conceptual, introducing the expansion-share limit as a policy framework, rather than a claim to the absolute numerical accuracy of the underlying emission factors. The modelling approach is primarily attributional, using average emission factors for the fuels supplied, with one consequential element: a marginal land-use-change (LUC) term applied to the additional feedstock induced by the B40-to-B50 switch. This treatment is made explicit because attributional and consequential choices can materially affect biofuel LCA outcomes (Nematian and Scown 2025).

The functional unit is one bank cubic metre (bcm) of overburden moved. Results are calculated internally as fuel-cycle carbon intensity in g CO_2e MJ^{-1} and then expressed per bcm using an energy-per-bcm conversion. The system boundary covers the liquid-fuel cycle: feedstock production, FAME conversion, and combustion in mobile equipment. Downstream coal combustion, coal-mine methane blasting, grid electricity, and equipment manufacturing are outside the boundary (Figure 1). Coal-mine overburden is used as a diesel-intensive stress-test denominator. Indonesian mining companies and contractors report overburden volumes in audited annual and sustainability disclosures, allowing the physical fuel-displacement effect to be expressed against an externally auditable activity measure rather than assumed in isolation (Adiansyah *et al.* 2017). The bcm denominator therefore affects the reporting scale, but not the LUC threshold.

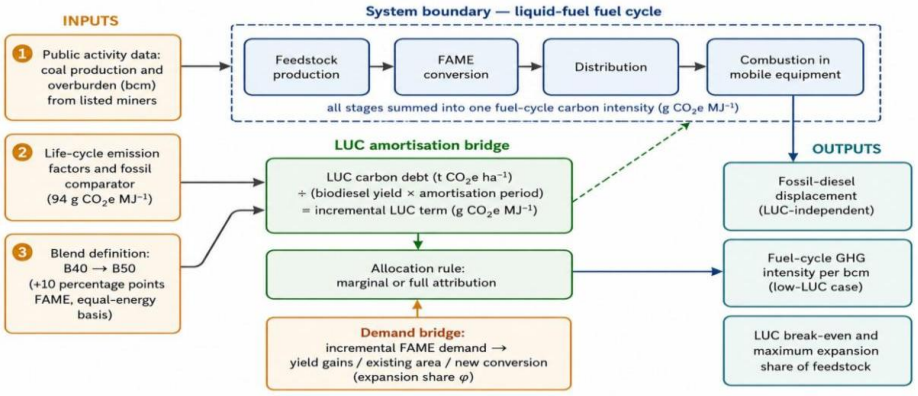


Figure 1 B40-to-B50 fuel-cycle screening framework and LUC sourcing bridges

Equal-energy comparison of B40 and B50

Palm biodiesel has a lower volumetric energy density than fossil diesel; comparing equal litres would therefore overstate the higher blend's fuel displacement. The model instead holds delivered energy per bcm constant using lower heating values LHV_d = 36 and LHV_f = 33 MJ L^{-1}. For a volumetric FAME fraction b, the blend energy density

and the FAME energy share are

$$H(b) = (1 - b)\cdot LHV_d + b\cdot LHV_f \quad (1)$$

$$x(b) = b\cdot LHV_f / H(b) (2)$$

With a B40 fuel-use intensity FI_{40} = 0.35 L bcm^{-1}, delivered energy per bcm is E = FI_{40}·H(0.40) = 12.180 MJ bcm^{-1} and the equal-energy B50 volume is V_{50} = E/H(0.50) = 0.3530 L bcm^{-1}, so fossil-diesel displacement follows deterministically:

$$\Delta_{diesel} = 0.60\cdot FI_{40} - 0.50\cdot V_{50} = 0.0335 \; L bcm^{-1} (3)$$

This is a first-order stoichiometric correction; it does not capture second-order changes in brake-specific fuel consumption (BSFC) when a high-FAME blend alters cetane number, oxygen content, and viscosity. Heavy-equipment testing of blends up to B35 indicates such effects are small (Uhanto *et al.* 2025), so the equal-energy result is treated as an idealised bound and a 0 to +3% BSFC penalty is carried as a sensitivity rather than modelled.

LUC break-even and allocation rules

LUC is treated as a forward-looking sensitivity on incremental supply. A converted hectare releases a carbon debt C_{debt} (t CO_2e ha^{-1}), equal to the loss of biomass, litter, and soil carbon relative to the prior ecosystem plus forgone sequestration, amortised over the plantation rotation:

$$L = C_{debt} / (Y_{bio} \times T) \quad (4)$$

with Y_{bio} the biodiesel energy yield (MJ ha^{-1} yr^{-1}) and T = 25 y, the period over which the land-use carbon debt is spread, matching the rotation over which the reference flux measurements were integrated (Meijide *et al.* 2020). For the 156 g CO_2e MJ^{-1} value, the underlying yield assumption is approximately 3.8 t CPO ha^{-1} yr^{-1}, corresponding to a FAME yield of Ybio ≈ 43 GJ ha^{-1} yr^{-1}; this is consistent with the Sumatran plantation studied by Meijide *et al.* (2020). The threshold is also recomputed at T = 20 and 30 y to show how it responds to this period. The measured high-LUC value for mineral-soil forest conversion is 156 g CO_2e MJ^{-1}, with peat conversion substantially higher because drained peat continues to oxidise and release stored carbon (ICCT 2011; Meijide *et al.* 2020). Peat conversion is not separately parameterised in the central scenario, as the focus is on mineral-soil forest conversion—the most extensively measured pathway for Indonesian palm expansion—and peat constitutes a distinct carbon pool with different management and drainage dynamics. Its exclusion means the high-LUC scenario is conservative; including peat would tighten the expansion-share limits further. Fuel-cycle emissions per bcm are the energy-weighted sum of the two intensities, with the LUC term applied only to the feedstock energy the switch newly induces:

$$G_{40} = E\cdot[(1 - x_{40})\cdot CI_d + x_{40}\cdot (5)$$

$$G_{50}(L) = E\cdot[(1 - x_{50})\cdot CI_d + x_{50}\cdot CI_f] + e_{inc}\cdot L \quad (6)$$

where G denotes fuel-cycle emissions per bcm, E the fuel energy used per bcm, CId and CIf the diesel and FAME intensities, and x the FAME energy share of the blend, with x_{40} = 0.3793 under B40 and x_{50} = 0.4783 under B50, and the bridging indicator

$$e_{inc} = E\cdot(x_{50} - x_{40}) = 1.205 \; MJ_{FAME} \; bcm^{-1} (7)$$

converts a per-MJ land term into a per-bcm quantity commensurable with the combustion ledger. The two ledgers are never differenced directly but summed into one intensity per blend. Setting G_{50}(L) = G_{40} gives the incremental-LUC break-even:

L = CId − CIf = 94 − 50 = 44 g CO_2eMJ^{-1} (8)*

Here CIf = 50 assumes methane capture at the mill; open-pond milling would raise the core intensity toward 76 g CO_2e MJ^{-1} and lower the break-even accordingly. The low-LUC case therefore depends on policies that promote POME methane capture *(8).*

Equation (8) has three implications for the analysis. First, the break-even LUC intensity is independent of the delivered energy per bcm, and therefore of fuel-use intensity, overburden volume, and the end-use selected for the stress test. The threshold intensity is also unaffected by the blend step and the lower heating values, though the absolute equivalent land area in Equations (10) and (11) still scales with it. No characteristic of the mining case can therefore shift the threshold; uncertainty in

L* comes only from the fossil-diesel comparator and the non-LUC palm-biodiesel core intensity. Across CI_f = 46–52 g CO_2e MJ^{-1} and CI_d = 89–99 g CO_2e MJ^{-1}, the resulting range is 37–53 g CO_2e MJ^{-1}. Second, applying the conversion debt symmetrically across all palm energy in both blends does not alter the break-even. Under this average rule, the difference between B40 and B50 reduces to $(x_{50} - x_{40})\cdot(CI_d - CI_f - L) = 0$, so the same threshold is obtained. This is because the same added palm intensity is applied to both blends, leaving their relative difference unchanged. Third, the threshold tightens only under an asymmetric full-attribution rule, in which the LUC term is charged to the entire B50 palm volume while the B40 palm volume is exempted. This rule answers a precautionary attribution question rather than the incremental B40-to-B50 question, but it provides a useful lower bound: $L^*_full = (1 - x_{40}/x_{50})\cdot(CI_d - CI_f)$ 9g CO_2e MJ^{-1}. Both the incremental and full-attribution bounds are therefore reported.

Feedstock balance and expansion share

The break-even identifies the LUC intensity that can be tolerated, but not the land pressure implied by the B40-to-B50 step. To close this gap, the incremental biodiesel demand is converted into a national feedstock balance. A full B50 mandate is estimated to require about 20.1 million kL yr^{-1} of biodiesel, compared with about 15.6 million kL yr^{-1} under B40, giving an increment of approximately 4.5 billion L yr^{-1} (Petromindo 2026). These volumes assume total diesel demand is held constant across the two blends; demand growth of a few percent per year would raise the increment and the additional CPO proportionally. Using a FAME density of 0.875 t kL^{-1} and a CPO-to-FAME mass ratio of 1.03, this increment requires about 4.06 Mt yr^{-1} of additional CPO.

$$\Delta M_{CPO} = \Delta V \cdot \rho \cdot r \approx 4.06\ \text{Mt CPO yr}^{-1} \quad (9)$$

$$A_{eq} = \Delta M_{CPO} / Y_{CPO} \quad (10)$$

$$\Delta MCPO = \Delta Myield + \Delta Mreallocated + YCPO \cdot Anew \quad (11)$$

Equation (10) converts the increment into the land-equivalent area at CPO yield Y_{CPO}; Equation (11) partitions it among yield-gap closure on existing area, reallocation from food and export, and new planted area A_{new}. Letting φ denote the share of incremental feedstock energy from newly converted high-carbon land, the effective incremental LUC intensity is $L_{eff} = \varphi \cdot L_{conv}$, and the switch stays beneficial while $L_{eff} < L^*$; setting $L_{eff} = L^*$ gives the maximum tolerable expansion share

$$\varphi^* = L^* / L_{conv} \quad (12)$$

This reframes the vague marginal LUC rate as a calculable theoretical quantity, following the European Commission's logic for high-ILUC-risk feedstocks in which a share-of-expansion threshold is obtained by dividing an emission saving by a conversion intensity (European Commission 2019a). φ is the scenario variable, not a known input: scenarios are φ = 0 (second-rotation replanting, degraded land, or intensification), φ = 0.14 (the Commission reference expansion share, European Commission 2019a; L_{eff} 22 g CO_2e MJ^{-1}), and φ = 1 (all incremental feedstock from mineral-soil forest conversion).

Data sources and sensitivity

Emission factors and the fossil comparator were taken from recognised lifecycle references, while activity denominators were drawn from audited public disclosures. The non-LUC palm-biodiesel core intensity is represented as 46–52 g CO_2e MJ^{-1} under a methane-capture milling pathway, with an open-pond pathway near 76 g CO_2e MJ^{-1} shown for comparison. The difference is driven mainly by palm-oil-mill-effluent (POME) methane management, and the stage decomposition is reported in Table 1 (Kalam and Masjuki 2002; Harsono *et al.* 2012; Singh *et al.* 2021). The fossil comparator is the RED II Annex V value of 94 g CO_2e MJ^{-1}, used only as a transparent reference point rather than as an Indonesian eligibility criterion (EU 2018). The bcm denominators are bracketed using a panel of listed miners and

contractors (Table 2). They are used to define a realistic stress-test range and are not aggregated into a sector-wide mining estimate. Fuel-use intensity is set at 0.35 L bcm^{-1} as a standardised literature-based assumption, not a fleet-measured value; because it drives the absolute per-bcm results, it is carried with a ±30% sensitivity band. Sensitivity tests vary one input at a time and cover the palm core intensity, fossil comparator, FAME heating value, brake-specific fuel-consumption penalty, fuel-use intensity, overburden volume, LUC time horizon T, allocation rule, and expansion share φ. All model inputs and ranges are summarised in Table 3.

Table 1 Indicative stage-level decomposition of the non-LUC palm-biodiesel core intensity.

Fuel-cycle stage	Indicative intensity	Main driver / interpretation
Cultivation, including fertiliser N_2O	14–20 g CO_2e MJ^{-1}	Field emissions from fertiliser use and plantation management; excludes historical direct LUC.
FFB transport to mill	1–3 g CO_2e MJ^{-1}	Short-haul-road transport from plantation to mill; relatively minor contribution.
Milling and CPO extraction	6–18 g CO_2e MJ^{-1}	Strongly influenced by POME management; methane capture gives the lower range, while open ponds raise emissions.
Transesterification	8–12 g CO_2e MJ^{-1}	Methanol input and process energy; glycerol co-product handled by energy allocation.
Distribution and blending	1–2 g CO_2e MJ^{-1}	Depot logistics and blending operations; relatively minor contribution.
Combustion	≈0 g CO_2e MJ^{-1}	Tailpipe biogenic CO_2 treated as carbon-neutral; non-CO_2 tailpipe emissions are small.
Core total, methane-capture pathway	46–52 g CO_2e MJ^{-1}	Non-LUC core intensity used in the low-LUC case; open-pond pathway shown separately at about 76 g CO_2e MJ^{-1}.

Notes: FFB = fresh fruit bunches; POME = palm-oil-mill effluent. Stage ranges are literature-consistent and sum to the 46–52 g CO_2e MJ^{-1} core (Kalam and Masjuki 2002; Harsono *et al.* 2012; Singh *et al.* 2021).

Table 2 Operational stress-test panel used to bracket the per-bcm denominators

Company	Coal (Mt)	Overburden (Mbcm)	Stripping ratio	Scope 1 (Mt CO_2e)
United Tractors / Pamapersada	148	1,217	8.2	-
Adaro Andalan	65.8	286	4.35	-
Indo Tambangraya	20.2	n.d.	10–11	1.82
Delta Dunia / BUMA	90	545	6.05	0.72
Bukit Asam	43.3	n.d.	5.98	-

n.d. = not disclosed. Sources: company annual and sustainability reports, financial year 2024. The panel is not used to infer whole-sector mining emissions.

Table 3 Key model inputs and scenario parameters used in the B40-to-B50 fuel-cycle screen.

Model input	Value / range	Unit	Role in the calculation
Fossil-diesel comparator	94	g CO_2e MJ^{-1}	Reference carbon intensity used for blend comparison and LUC break-even calculation.
Palm-biodiesel core intensity, methane-capture pathway	46–52	g CO_2e MJ^{-1}	Non-LUC palm-biodiesel intensity under methane capture; used as the low-LUC core assumption.
Palm-biodiesel core intensity, open-pond pathway	76	g CO_2e MJ^{-1}	Higher-intensity processing pathway shown for comparison.
Blend definition	B40 = 40%; B50 = 50%	vol. FAME	Defines the additional ten percentage points of FAME in the B40-to-B50 switch.
Lower heating value	Diesel = 36; FAME = 33	MJ L^{-1}	Converts the blend comparison to an equal-energy basis.
Fuel-use intensity	0.35 ± 30%	L bcm^{-1}	Standardised operating assumption used to express results per bcm; not site-measured.
LUC amortisation period, T	25; sensitivity 20–30	years	Converts one-time land-conversion debt into a per-MJ LUC intensity.
Incremental LUC scenarios	0; 22; 156	g CO_2e MJ^{-1}	Represents low-LUC, moderate expansion-share, and forest-conversion-equivalent sourcing cases.
Allocation rule	Marginal; symmetric average; full attribution	—	Determines how LUC is assigned to palm energy; marginal and symmetric average give $L^* \approx 44$, while full attribution gives ≈9 g CO_2e MJ^{-1}.
Incremental FAME-energy bridge, e_inc	1.205	MJ_FAME bcm^{-1}	Converts a per-MJ incremental LUC term into a per-bcm land-use penalty.
Incremental CPO requirement	4.06	Mt yr^{-1}	Converts the B40-to-B50 volume step into additional feedstock demand.
Expansion share, φ	0–100	%	Share of incremental feedstock supplied from new high-carbon conversion.

RESULTS AND DISCUSSION

Fossil-diesel displacement is robust and LUC-independent

Holding delivered energy per bcm constant, B50 requires slightly more total liquid fuel than B40 because FAME has a lower energy density, but the fossil-diesel share falls as the blend increases (Figure 2). Relative to B40, B50 displaces 0.0335 L of fossil diesel per bcm, with a range of 0.023–0.044 L bcm^{-1} across the ±30% fuel-intensity band. This displacement follows only from the blend ratio and the equal-energy correction. It therefore supports the mandate's import-substitution rationale at the operation level.

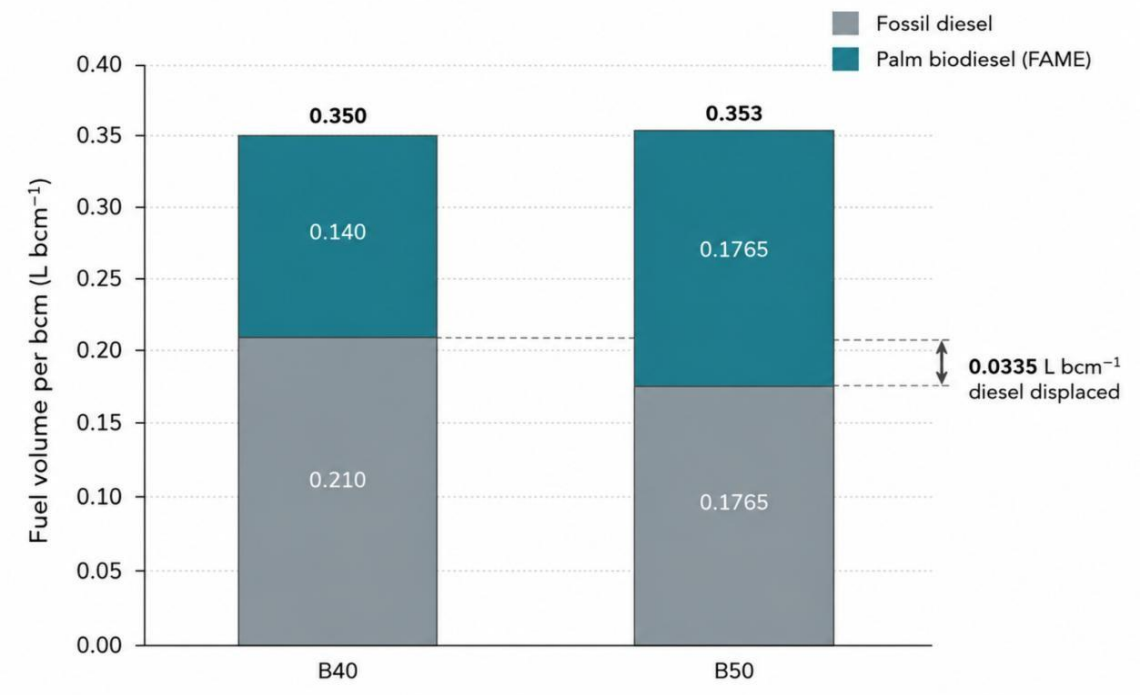


Figure 2 Equal-energy fuel composition of B40 and B50 per bank cubic metre of overburden moved

The LUC break-even defines the climate boundary

The climate benefit is bounded by an incremental-LUC break-even of 44 g CO_2e MJ^{-1}, with a range of 42–48 across the palm core-intensity assumption and 37–53 when the fossil comparator is also varied (Figure 3). As Equation (8) shows, the threshold depends only on the fossil comparator and the non-LUC palm core intensity; fuel-use

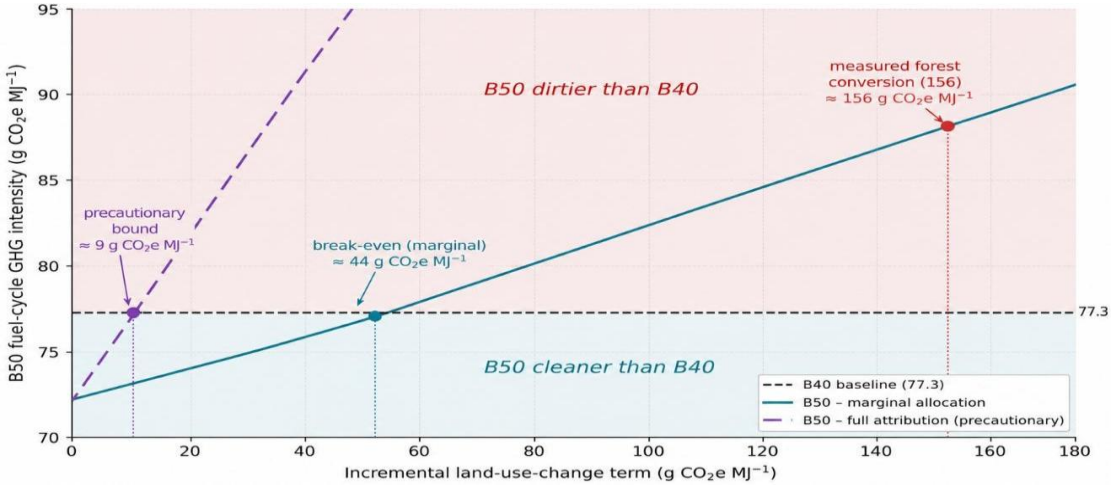


Figure 3 Land-use-change (LUC) break-even for the B40-to-B50 switch.

intensity, overburden volume, and heating values do not change it. Under the precautionary full-attribution rule, the tolerance tightens to about 9 g CO_2e MJ^{-1}. At the measured mineral-soil forest-conversion intensity of 156 g CO_2e MJ^{-1}, the land penalty is 188 g CO_2e bcm^{-1}, exceeding the 53 g CO_2e bcm^{-1} combustion-side saving and producing a net increase of 135 g CO_2e bcm^{-1}. This corresponds to the gap between 1.077 and 0.942 kg CO_2e bcm^{-1} in Figure 4. Forest-conversion sourcing therefore exceeds both thresholds and reverses the low-LUC climate benefit, consistent with palm-biodiesel studies showing that LUC can be a sign-reversing rather than marginal term (de Souza *et al.* 2010; Searchinger *et al.* 2008; Harsono *et al.* 2012; Meijide *et al.* 2020).

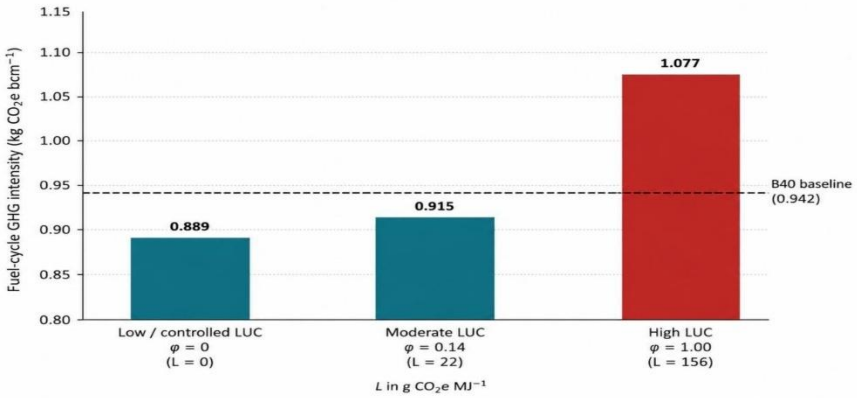


Figure 4 B50 fuel-cycle GHG intensity under incremental LUC scenarios

The expansion-share limit makes the boundary policy-relevant

Translating the break-even through Equation (12) gives the main policy-relevant quantity of the study. If a share φ of incremental feedstock is supplied from land converted at 156 g CO_2e MJ^{-1}, the switch remains beneficial only while $\varphi < \varphi^* = L^*/156$. This gives a maximum tolerable expansion share of 28% under the marginal rule and 6% under full attribution (Figure 5). Put differently, the fuel-cycle benefit is lost once more than 28% of the additional CPO for B50, or 6% under precautionary accounting, comes from forest-conversion-equivalent land. The break-even is therefore converted from a carbon-intensity threshold into a monitorable sourcing condition. This is the more useful policy question: not only whether 156 exceeds 44, but how much high-carbon expansion the B40-to-B50 step can absorb before its climate benefit is lost. The threshold sets the boundary but does not by itself show that the actual expansion share lies below it.

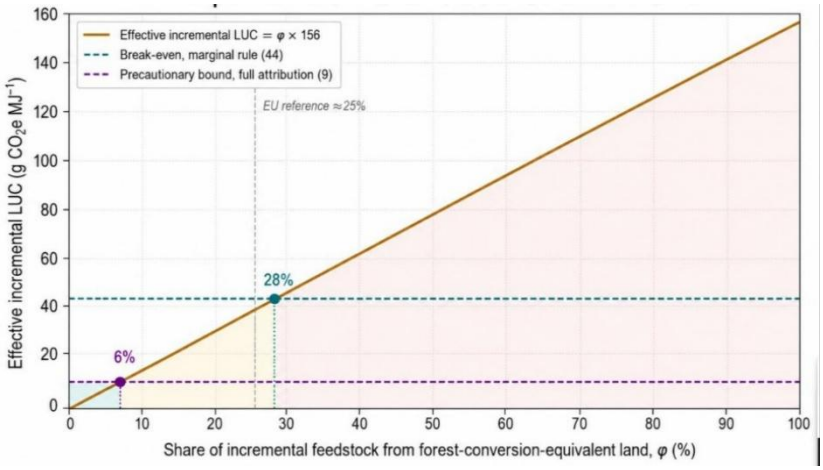


Figure 5 Expansion-share limit for incremental B50 feedstock

The feedstock balance shows low-LUC supply cannot be assumed

The expansion share must be read against the physical supply requirement of the B40-to-B50 step (Table 4). The incremental mandate implies ΔM_CPO ≈ 4.06 Mt yr^{-1} of additional CPO (Equation 9), consistent with market estimates of 3.5–4.0 Mt yr^{-1} (S&P Global 2025). Depending on yield assumptions, this is equivalent to 1.26, 1.07, or 0.92 Mha of land-equivalent output at the all-planted-area yield, the mature-stand average, or a 22% improved yield, respectively (Equation 10). they show the scale of supply that must be met through yield improvement, reallocation from food or export markets, or new planted area. the incremental requirement is too large to be treated as automatically low-LUC. Expansion alone cannot supply the step on the mandate timeline, while the required supply gain exceeds what replanting is currently delivering (Woittiez *et al.* 2017). The remaining adjustment would have to come from existing uses, principally food and export markets; ΔM_CPO is equivalent to about 41% of the 9.83 Mt of CPO used domestically for food in 2025 (GAPKI 2026; USDA FAS 2026). This reallocation channel is why a direct-LUC break-even

Table 4 Incremental feedstock requirement and land-equivalent supply implied by the B40-to-B50 step

Quantity	Value	Unit	Source / derivation
Biodiesel volume under B40	15.6	million kL yr^{-1}	ESDM estimate reported in Petromindo (2026).
Biodiesel volume under B50	20.1	million kL yr^{-1}	ESDM estimate reported in Petromindo (2026).
Incremental biodiesel volume, ΔV	4.5	billion L yr^{-1}	Difference between B50 and B40 biodiesel requirements.
FAME density, ρ	0.875	t kL^{-1}	Standard FAME density assumption.
CPO-to-FAME mass ratio, r	1.03	t CPO t^{-1} FAME	Based on an approximate 97% transesterification mass yield.
Incremental CPO requirement, ΔM_CPO	4.06	Mt yr^{-1}	Calculated from Eq. (9); comparable with the 3.5–4.0 Mt yr^{-1} estimate reported by S&P Global (2025).
CPO yield, Y_CPO	3.23 / 3.80 / 4.40	t ha^{-1} yr^{-1}	National planted-area yield; mature-stand average; and 22% yield-uplift case.
Land-equivalent output, A_eq	1.26 / 1.07 / 0.92	Mha	Calculated from Eq. (10) using the three yield assumptions above.
Observed net planted-area expansion	<0.15	Mha yr^{-1}	USDA FAS (2026).
National replanting programme delivered	<0.05	Mha yr^{-1}	USDA FAS (2026).
Domestic CPO use for food, 2025	9.83	Mt yr^{-1}	GAPKI (2026); ΔM_CPO is approximately 41% of this volume.
Domestic CPO use for biodiesel, 2025	12.70	Mt yr^{-1}	GAPKI (2026); reported as increasing by 11.0% year-on-year under B40.

alone is incomplete. Diverting CPO from food or export markets does not place direct land conversion on the biodiesel ledger, but it can transfer supply pressure elsewhere. Regulatory practice also indicates that the omitted indirect term can be material. That value already exceeds the 44 g CO_2e MJ^{-1} break-even before direct conversion is added. Low-LUC sourcing therefore needs to be verified through supply-chain traceability and certification, not assumed.

Sourcing safeguards and the upstream role of smallholders and SMEs

The break-even and expansion-share limit together define the sourcing condition for B50: incremental feedstock must remain below the LUC, either through existing planted area, yield gains, or verified low-deforestation-risk supply.The model establishes the displacement rate and carbon threshold; the link to sourcing is an interpretation based on secondary evidence on Indonesian oil-palm governance. Because Indonesia manages land conversion through legality, spatial planning, ISPO, RSPO, and traceability instruments rather than a fuel-carbon score, the relevant safeguards are administrative and supply-chain based (Table 5).

Table 5 Supply-chain safeguards for maintaining low-LUC incremental feedstock for B50 palm biodiesel

Safeguard	**Relevance to low-LUC B50 sourcing**	**Smallholder / SME role**	**Indonesian mechanism**
Legal land status	Reduces the risk that incremental feedstock is sourced from unlawful or high-conversion-risk areas.	Provide plot documentation and participate in registration or aggregator-based verification.	STDB; APL / forest-estate distinction; ISPO legality requirements.
No forest or peat expansion	Prevents sourcing from high-carbon conversion that would exceed the LUC break-even.	Avoid new planting in forest or peat areas and supply through screened value chains.	Primary-forest and peatland moratorium; RSPO / NDPE commitments.
Documented sourcing to mill or plot	Helps distinguish feedstock from existing or productivity-based supply from expansion-driven supply.	Share plot and supply-chain data through cooperatives, mills, or SME service providers.	STDB / e-STDB; traceability-to-mill and, where feasible, traceability-to-plot systems.
Replanting and yield improvement	Increases feedstock availability without proportional spatial expansion, thereby lowering φ.	Adopt replanting, improved seedlings, and good agricultural practices where support is available.	Smallholder replanting programmes; extension services; cooperative aggregation.
Certification access	Provides documentation of legality and management practices, while not by itself proving low-LUC supply.	Participate through group certification, cooperatives, or SME-supported compliance services.	ISPO and RSPO smallholder certification approaches.

APL = Areal Penggunaan Lain or non-forest land; NDPE = No Deforestation, No Peat, No Exploitation; STDB = Surat Tanda Daftar Budidaya or cultivation registration. These safeguards can reduce LUC risk by improving legality, documentation, and traceability, but they should not be interpreted as automatic proof of low-LUC sourcing or as evidence of welfare improvement (Carlson et al. 2018; Santika et al. 2021).

Smallholders and SMEs matter within this upstream layer. They can support plot documentation, group certification, aggregation, replanting, and yield improvement, all of which can help reduce the expansion share of marginal supply. This role should be interpreted cautiously. Independent smallholders vary widely in land status, market access, productivity, and certification readiness (Jelsma *et al.* 2017), and yield-gap closure can increase supply without proportional land expansion only where replanting, inputs, and technical support are effective (Woittiez *et al.* 2017). Certification and documentation can reduce LUC risk, but they do not automatically prove low-LUC sourcing or generate welfare gains (Carlson *et al.* 2018; Santika *et al.* 2021).

Limitations

Several limitations frame the interpretation of the results. First, the model is a scenario-based operational fuel-cycle screen using published emission factors, not a full reviewed life-cycle assessment, and no field measurements were collected. The fuel-use intensity of 0.35 L bcm^{-1} is a standardised assumption carried at ±30%; it scales the per-bcm results but, by Equation (8), does not affect the LUC break-even. Second, the equal-energy comparison is a first-order correction. Potential changes in brake-specific fuel consumption are bounded through a 0 to +3% sensitivity range rather than modelled from equipment-specific data. Third, the LUC scenarios are sensitivity tests of incremental expansion risk, not predictions of actual sourcing. The 156 g CO_2e MJ^{-1} value represents one measured mineral-soil conversion case in Sumatra, and peat conversion is not separately parameterised. Fourth, the link to sourcing and the smallholder role are interpretive: no primary data were collected for this link, and the study does not model income, welfare, or supply-chain outcomes.

The analysis also does not model indirect land-use change endogenously. The RED II Annex VIII value is used only as a bounding reference; a consequential CPO-market model would be needed to estimate how food, export, and biodiesel demand interact. Coal mining is used only as a diesel-intensive activity denominator and should not be interpreted as representative of all B50 end uses. Future work should therefore prioritise spatially explicit concession and moratorium mapping to estimate φ directly, fleet telemetry to replace the fuel-intensity assumption, engine-dynamometer testing of B50 under mining duty cycles, and consequential modelling of the CPO market.

CONCLUSION

In the mining stress test, the B40-to-B50 switch reduces fossil-diesel use by about 0.0335 L bcm^{-1}, with the absolute value scaling by ±30% under the fuel-intensity assumption. This displacement is independent of land-use assumptions and therefore supports the mandate's import-substitution rationale rather than its climate rationale. The fuel-cycle GHG benefit is conditional. Under low-LUC sourcing, B50 reduces GHG intensity by about 5.6%, falling to roughly 2.8% if a 3% engine-efficiency penalty is realised. The benefit disappears once the incremental LUC term exceeds about 44 g CO_2e MJ^{-1}, or about 9 g CO_2e MJ^{-1} under precautionary full attribution. Expressed as a sourcing condition, the switch can tolerate at most about 28% of incremental feedstock from forest-conversion-equivalent land under the marginal rule, or about 6% under full attribution. Measured mineral-soil forest conversion at 156 g CO_2e MJ^{-1} exceeds both bounds, while the RED II provisional oil-crop iLUC value of 55 g CO_2e MJ^{-1} exceeds the marginal break-even before any direct conversion is counted.

The policy implication is that the climate value of higher blends depends less on the blend ratio itself than on the expansion share of marginal feedstock. This matters because Indonesia governs land conversion mainly through legality, certification, and traceability rather than a fuel-carbon score, and because the B40-to-B50 step implies about 4.06 Mt yr^{-1} of additional CPO, equivalent to roughly 41% of domestic food consumption. Keeping the

expansion share low would require traceable low-LUC sourcing through yield improvement, replanting, verified supply from existing planted areas, and safeguards against forest or peat conversion, with smallholders and SME aggregators playing an upstream role. A practical implication is that reporting the new-conversion share of incremental mandate feedstock against a declared ceiling near φ* could complement blend-volume targets and provide a clearer decision boundary. Future work should estimate φ directly from concession, moratorium, and land-cover data, validate fuel-use intensity using fleet telemetry, and model CPO food–fuel allocation consequentially so that iLUC enters endogenously. The mining case provides an auditable operational stress test and should not be read as evidence that coal mining becomes low carbon.

REFERENCES

Adiansyah JS, Haque N, Rosano M, Biswas W. 2017. Application of a life cycle assessment to compare environmental performance in coal mine tailings management. J Environ Manage. 199:181–191. DOI:10.1016/j.jenvman.2017.05.050.

Aguirre-Villegas HA, Benson CH. 2017. Case history of environmental impacts of an Indonesian coal supply chain. J Clean Prod. 157:47–56. DOI:10.1016/j.jclepro.2017.03.232.

[BPS] Badan Pusat Statistik. 2025. Indonesian permanent estate crops statistics. 2024. Jakarta (ID): Statistics Indonesia.

Carlson KM, Heilmayr R, Gibbs HK, Noojipady P, Burns DN, Morton DC, Walker NF, Paoli GD, Kremen C. 2018. Effect of oil palm sustainability certification on deforestation and fire in Indonesia. Proc Natl Acad Sci USA. 115(1):121–126. DOI:10.1073/pnas.1704728114.

Chain Reaction Research. 2022. The chain: how limited supply, alleged corruption, and the biodiesel market led to Indonesia's cooking oil crisis. Washington (DC): Chain Reaction Research; [accessed 2026 Jul 10].https://chainreactionresearch.com.

de Souza SP, Pacca S, de Avila MT, Borges JLB. 2010. Greenhouse gas emissions and energy balance of palm oil biofuel. Renew Energy. 35(11):2552–2561. DOI:10.1016/j.renene.2010.03.028.

[ESDM] Ministry of Energy and Mineral Resources. 2025. Mandatory B40 effective 1 January 2025 and Regulation No. 4/2025 on commercial biofuel blending. Jakarta (ID): ESDM.

European Commission. 2019a. Report on the status of production expansion of relevant food and feed crops worldwide. COM(2019) 142 final. Brussels (BE): European Commission.

European Commission. 2019b. Commission Delegated Regulation (EU) 2019/807 supplementing Directive (EU) 2018/2001 as regards high indirect-land-use-change-risk feedstock and the certification of low indirect-land-use-change-risk biofuels. Off J Eur Union. CELEX:32019R0807.

European Union. 2018. Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources. Off J Eur Union. Annex V. CELEX:32018L2001.

Fulcrum. 2022. Indonesia's cooking oil crisis: causes and consequences. Singapore (SG): ISEAS–Yusof Ishak Institute; [accessed 2026 Jul 10]. https://fulcrum.sg.

[GAPKI] Gabungan Pengusaha Kelapa Sawit Indonesia. 2026. Performance of the Indonesian palm oil industry 2025 and outlook for 2026. Jakarta (ID): GAPKI.

Halimatussadiah A, Nainggolan D, Yui S, Moeis FR, Siregar AA. 2021. Progressive biodiesel policy in Indonesia: does the government's economic proposition hold? Renew Sustain Energy Rev. 150:111431. DOI: 10.1016/j.rser.2021.111431.

Harahap F, Silveira S, Khatiwada D. 2019. Evaluating the palm oil demand in

Indonesia: production trends, yields, and emerging issues. Biofuels. 10(1):23–38.

Harsono SS, Prochnow A, Grundmann P, Hansen A, Hallmann C. 2012. Energy balances and greenhouse gas emissions of palm oil biodiesel in Indonesia. GCB Bioenergy. 4(2):213–228. DOI: 10.1111/j.1757-1707.2011.01118.x.

[ICCT] International Council on Clean Transportation. 2011. Review of peat surface greenhouse gas emissions from oil palm plantations in Southeast Asia.Washington (DC): ICCT. Jelsma I, Schoneveld GC, Zoomers A, van Westen ACM. 2017. Unpacking Indonesia's independent oil palm smallholders: an actor-disaggregated approach to identifying environmental and social performance challenges. Land Use Policy. 69:281–297. DOI: 10.1016/j.landusepol.2017.08.012.

Kalam MA, Masjuki HH. 2002. Biodiesel from palm oil – an analysis of its properties and potential. Biomass Bioenergy. 23(6):471–479. DOI: 10.1016/S0961-9534(02)00085-5.

Meijide A, de la Rua C, Guillaume T, Roll A, Hassler E, Stiegler C, Tjoa A, June T, Corre MD, Veldkamp E, Knohl A. 2020. Measured greenhouse gas budgets challenge emission savings from palm-oil biodiesel. Nat Commun. 11:1089. DOI: 10.1038/s41467-020-14852-6.

Nematian M, Scown CD. 2025. Advances and emerging issues in life-cycle assessment for biofuel policy. GCB Bioenergy. 17(8):e70061. DOI: 10.1111/gcbb.70061.

Petromindo. 2026. Indonesia delays B50 biodiesel mandate, maintains B40, and raises palm oil export levy. Jakarta (ID): Petromindo.

Reuters. 2026. Indonesia scraps plan to introduce B50 biodiesel this year, will raise palm oil export levy. London (UK).

Palm Oil. 2018. RSPO principles and criteria for the production of sustainable palm oil. Kuala Lumpur (MY): RSPO.

Sahara, Dermawan A, Amaliah S, Irawan T, Dilla S. 2022. Economic impacts of biodiesel policy in Indonesia: a computable general equilibrium approach. J Econ Struct. 11(1):22. DOI: 10.1186/s40008-022-00281-9.

Santika T, Wilson KA, Law EA, St John FAV, Carlson KM, Gibbs H, Morgans CL, Ancrenaz M, Meijaard E, Struebig MJ. 2021. Impact of palm oil sustainability certification on village well-being and poverty in Indonesia. Nat Sustain. 4:109–119. DOI: 10.1038/s41893-020-00630-1.

Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D, Yu TH. 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. Science. 319(5867):1238–1240. DOI: 10.1126/science.1151861.

Singh D, Sharma D, Soni SL, Inda CS, Sharma S, Sharma PK, Jhalani A. 2021. A comprehensive review on 1st-generation biodiesel feedstock palm oil: production, engine performance, and exhaust emissions. BioEnergy Res. 14:1–22. DOI: 10.1007/s12155-020-10171-2.

S&P Global. 2025. Indonesia keeps 2026 biodiesel quota flat, raising doubts over B50 target. Platts Agric News.

Uhanto U, Yandri E, Hilmi E, Saiful R, Ariati R. 2025. Evaluating engine durability and operational effects of biodiesel blends in heavy equipment applications. Next Energy. 9:100392. DOI: 10.1016/j.nxener.2025.100392.

[USDA FAS] United States Department of Agriculture, Foreign Agricultural Service. 2026. Oilseeds and products annual: Indonesia. Report ID2026 0013. Jakarta (ID): USDA FAS.

Woittiez LS, van Wijk MT, Slingerland M, van Noordwijk M, Giller KE. 2017. Yield gaps in oil palm: a quantitative review of contributing factors. Eur J Agron. 83:57–77. DOI: 10.1016/j.eja.2016.11.002.