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# Palm oil biofuels demystification: The needs of standardized life cycle assessments and source derivatization

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## Abstract

The implementation of binary renewable-versus-fossil policy frameworks has the effect of obscuring the environmental costs and overstating the sustainability of palm oil biofuel. This review examines life cycle assessment (LCA) studies and regulatory frameworks, demonstrating that land-use change (LUC) is the predominant source of greenhouse gas and deforestation poses a threat to over 80% of species in production regions. Inconsistent system boundaries have been found to hinder comparability, with certification schemes including RSPO, ISPO, and EU RED II frequently overlooking LUC data, thus perpetuating unsustainable plantation strategies. As one of the most imminent solutions, used cooking oil (UCO) appears as a viable alternative, exhibiting a carbon intensity that is more than 60 % lower than that of conventional jet fuel and potentially resulting in a reduced depletion of fossil resources. However, only approximately 20% of global domestic UCO is recycled and 85% of regions lack UCO-specific legislation. A three-pillar framework is proposed: harmonized LCA with mandatory LUC accounting, scaled UCO valorization, and biodiversity-friendly practices including agroforestry and castor cultivation on degraded lands. It is reported that these measures can reduce emissions by 67.2% without compromising land integrity or food security. The notion of directly comparing the non-use of palm oil with the complete disregard for its unsustainability may be alleviated in the future by regarding some of the aspects proposed in this study.

*Keywords: Palm oil; LCA; green washing; mitigation; used cooking oil; sustainable certification*

## 1. Introduction

The global economic downturn has a disrupted effect on industries, causing price and supply chain instability in the transportation fuel sector[1]. In this scenario, the transition from fossil-based fuels to renewable fuels is crucial for ensuring long-term energy sustainability[2]. This review discusses the essential steps required by palm oil industries to take to thrive as competitive alternative fuel providers. Despite the well documented environmental benefits of biofuels, including potential carbon neutrality, biodegradability, and cleaner emissions, economic barriers and negative environmental effects continue to inhibit their widespread commercialization. This underscores the necessity of transitioning from fossil fuels to renewable energy sources to ensure sustained energy security. Palm oil-based fuel is a first-generation biofuel feedstock owing to its reported high yield efficiency, established supply chains, and economic significance in Southeast Asia. Despite the environmental advantages of biofuels, including carbon neutrality and cleaner emissions, economic challenges and certain negative environmental impacts restrict their widespread use. As a solution to the impending biofuel-related issues, this review posits that it is critical for the palm oil industries to harness their strengths effectively and contribute to the advancement of renewable energy initiatives.

It is imperative to recognize the urgent need to shift from traditional crop-based feedstocks, as they are in direct conflict with the delicate balance of anthropogenic hydrogeology and carbon debt due to land-use change. The potential for LUC to cause significant carbon debt is dependent upon the original type. The typical carbon debt resulting from conversion of lowland tropical rainforest into palm oil plantations is estimated to be approximately 610 Mg $CO_2$/ha. The time required to repay this amount of released carbon would be approximately 86 years [3]. Conversely, the release of carbon into a peatland may amount to approximately 3000 Mg $CO_2$/ha, a process that is

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estimated to require around 420 years to repay[4]. In several of the world's leading palm oil-producing countries, aggressive canalization and artificial drainage of tropical peatlands have drastically disrupted regional hydrology[5–7]. This disruption is not a minor inconvenience; it triggers oxidative peat decomposition and causes ground subsidence at alarming rates of several centimeters per year, whilst significantly enhancing greenhouse gas emissions. This unpleasant fact highlights that current conventional plantation models undeniably are not sustainable ones. A decisive and strategic shift is essential to decouple fuel production from land-intensive practices that impair its foundation. Thus, it is critical that immediate intervention is undertaken to ensure the preservation of the environment and the establishment of a sustainable future for the region.

Beyond the latent risks of uncontrolled expansion of palm oil plantations, a gap also needs to be bridged between the promising closed carbon cycle of the future and the apparent immediate release of hydrogeological ecosystem and stored carbon prior to a complete transition of fuel resources to this plantation. A prudent strategy is required for the sustainable expansion of palm oil plantations with a view to reducing environmental impacts. An interesting report describes how the carbon debt saved from the utilization of vegetable oil in biofuel is far less when contrasted with the immediate carbon debt from plantation practices.[8]. Thus, balancing the apparent ecological risks with long-term carbon sequestration is essential to harness the renewable potential of palm oil in the future.

Despite the environmental impact outlined above, it is critical to recognize the substantial positive contributions of oil palm plantations to rural development, economic prosperity and food security in producing countries. Globally, palm oil has been identified as the most productive vegetable oil crop, exhibiting an outstanding land-use efficiency of approximately 3.7 tonnes of oil per hectare per year. This is in comparison to soybean (0.4 t/ha) and sunflower (0.6 t/ha), which require significantly more land to satisfy the equivalent demand [9,10]. This productivity advantage is reflected in significant economic gains. In Malaysia, palm oil contributed to 2.7 % of the national GDP in 2020. In Indonesia, as the largest producer of palm oil, the industry provides livelihoods for approximately 3.5 million smallholder farmers and offers direct employment to over 4 million individuals, with a further 10 million employed indirectly. [11,12]. It is reported that smallholder farmers cultivating palm oil have experienced 30–45% increase in household income, with annual earnings reaching USD 4,633 to USD 5,500. This is substantially higher than the income of non-palm oil farmers and has contributed to a reduction in rural poverty of up to 45% in key producing regions [13–15]. Beyond income generation, palm oil cultivation has been associated with improvements in human capital formation, including enhanced access to education, healthcare, housing, and basic utilities, as well as increased dietary diversity and consumption of essential nutrients within smallholder households [16,17]. The industry has been shown to produce substantial fiscal revenues for producing the countries (for instance, Indonesia's palm oil exports alone were valued at USD 20.8 billion in 2019) and has been demonstrated to promote regional economic development by means of improving infrastructure and creating small businesses. From an environmental perspective, mature palm oil plantations on mineral soils (not recently converted from forests or peatlands), when managed sustainably, have the potential for carbon sequestration up to 116.7 Mg Carbon/ha in intercropping systems, and certified sustainable operations have achieved about 25% reduction in GHG emission compared to conventional practices [18,19]. Palm oil agroforestry systems integrating native trees or other crops have been shown to exhibit Land Equivalent Ratios exceeding 1.0, thereby enhancing biodiversity while maintaining economic returns [20,21]. Furthermore, the palm oil industry has been found to contribute positively to a minimum of 15 United Nations Sustainable Development Goals, particularly SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 5 (Gender Equality through employment opportunities for women), and SDG 8 (Decent Work and Economic Growth) [22–24]. The positive socio-economic and environmental aspects of palm oil production demonstrate that, in principle, palm oil is not necessarily inherently unsustainable. However, the impacts of palm oil production are critically dependent on management practices, governance frameworks and the ecological context of plantation establishment – a balancing act discussed in more detail in the mitigation strategies of the latter sections of this review.

In real applications, several practical methods for optimizing palm oil production have been identified, including location-based optimization, harvest management, and production technology optimization. These strategies rely heavily on direct technological advancements in the field of palm oil production equipment. It is evident that these approaches are promising for advanced industries and institutions that are engaged in the operation of palm oil production facilities in the future. However, for underdeveloped institutions or small farm holders, such approaches may pose significant challenges in terms of capital and operating expenditures. Therefore, it is recommended that a more holistic approach be explored, one which regulates plantation practices through farmer engagement, using a socioeconomic framework.

Despite being frequently categorized as non-technological approaches, socio-economic strategies play an essential role in the success of palm oil optimization initiatives in Malaysia. The progression is facilitated by partnership models, such as the Nucleus-Estate scheme, which professionalizes independent farmers through cooperatives, in conjunction with indirect digital literacy advancement[25,26]. In this context, the utilization of artificial intelligence and blockchain technologies provide the transparency mandated by the EUDR (European Union Deforestation Regulation), thereby generating employment opportunities of a high skill set, which are essential in the retention of rural youth. The positive socio-economic and environmental attributes of palm oil production highlight that it is not necessarily inherently unsustainable. However, the impacts of palm oil production are critically dependent on management practices, governance frameworks and the ecological context of plantation establishment. This is a balancing act discussed in the mitigation strategies of the latter sections of this review.

As previously referenced, technological and feedstock evolution within the palm oil industry is required to alleviate positive environmental and socioeconomic conditions. These advancements have the potential to enhance efficiency in production processes and reduce the environmental impact. The integration of sustainable practices with innovative technologies has been demonstrated to enhance industry competitiveness while supporting local communities. Furthermore, the adoption of cleaner feedstock alternatives have the potential to make a significant contribution to climate change mitigation. In terms of the practical implementation of this initiative, the utilization of mechanized farming, the use of Internet of Things[27], usage of high-yield palm oil plantation varieties[28], the integration of palm oil with selected plantation[29], the implementation of integrated biorefinery[30], and utilization of Used Cooking Oil (UCO) and algae-based biofuel have been identified as the most effective strategies [31,32].

Another effort to mitigate the negative effects of palm oil plantations is to enforce appropriate regulations on plantation practices. To date, at least four commonly utilized regulatory standards have been identified to maintain the sustainability of palm oil plantations. In this case, the Roundtable on Sustainable Palm Oil (RSPO), Indonesian Sustainable Palm Oil (ISPO), Malaysian Sustainable Palm Oil (MSPO), and Renewable Energy Directive II (RED II) by the European Union are among the major known regulations. In essence, RSPO, MSPO, and ISPO are regulations that have comparable emphasis on the sustainability of palm oil in terms of overall production processes. In addition to the two aforementioned regulations, RED II emphasizes indirect land-use change (ILUC), with the objective of further hindering land conversion and immediate carbon release from peatlands. In practice, these three regulations have been shown to have significant effect on the price of crude palm oil[33].

A critical aspect that must be thoroughly examined in any mitigation approach is the accurate collection and reporting of Life Cycle Assessment (LCA) data. This aspect should encompass comprehensive data on the inputs, outputs, and environmental impacts associated with each phase of a product or process life cycle. The credibility and reproducibility are dependent upon the transparency of its method and underlying assumptions. Furthermore, the utilization of transparent reporting allows for comparisons between studies, thereby facilitating the informed decision-making process concerning mitigation strategies. In the context of legalized carbon credit transactions, the credibility of the LCA is crucial for accurate reporting and, thus, proper certification. Regarding palm oil production, LCA is essential to address the overlooked effects such as Land Use Change (LUC), loss of biodiversity and socio-economic impacts. While some major reports in palm oil-producing countries continue to focus heavily on carbon footprint, this oversight creates opportunities for the enhancement of LCAs[34].

The review addresses several aspects related to the sustainability and assessment of palm oil production and its alternatives. The present study initiated with a comparison of refined palm oil with biofuel sources of the next generation, including algal oil and UCO. It was followed by an assessment of their environmental impacts, economic feasibility and potential for large-scale implementation. The objective of this comparative analysis is to clarify the advantages and limitations of each oil type, particularly in terms of resource efficiency, carbon footprint and their contribution to the circular economy. It is therefore essential to identify more sustainable feedstocks that would contribute towards reducing the dependency on traditional palm oil, which is often linked to significant ecological degradation.

Furthermore, this review critically assesses the current sustainability standards and policies that govern palm oil production in major producer countries such as Malaysia and Indonesia. It then proceeds to analyze the apparent differences in sustainability aspects between these countries and the European union as one of the highest consumers of palm oil. The analysis employed in the review extends to identifying deficiencies and weaknesses in existing regulations, including enforcement challenges and regional inconsistencies. This review ultimately puts forward the argument for comprehensive sustainable frameworks that integrate environmental, economic, and social dimensions. The purpose of such framework is to address the multifaceted consequences of palm oil plantations more effectively. These frameworks emphasize comprehensive mitigation strategies, stakeholder engagement, and adaptive policy mechanisms to ensure long-term sustainability and equity.

## 2. Biofuel Feedstock Hierarchy: from Palm Oil to next-gen Sources

The conventional representation of the biofuel feedstock hierarchy, from 1G food crops to 4G synthetic biology platforms, is one of the linear progressions towards sustainability. This framing, however, conceals a fundamental paradox: the unparalleled land-use efficiency of palm oil (3.3–3.6 t oil/ha, four to eight times higher than soy, rapeseed or sunflower) should, in theory, minimize total land pressure and associated environmental impacts. Nevertheless, palm oil remains the primary driver of tropical deforestation and biodiversity loss in Southeast Asia. To understand the reasons why efficiency gains have not been reflected in environmental protection, we have interrogated three structural barriers locking the biofuel sector into unsustainable 1G feedstocks despite clear sustainability imperatives. Firstly, economic lock-in feedstock costs are up to 95% of production costs, resulting in path dependency on existing 1G supply chains and making the transition to more expensive advanced feedstocks economically unappealing without significant carbon pricing. Secondly, infrastructure mismatch is evident. Existing refineries are optimized for 1G feedstocks, and retrofitting for 2G/3G requires capital investment that current carbon pricing does not incentivize. Thirdly, policy failure is evident in the reliance of certification schemes (RSPO, ISPO) rely on process verification rather than outcome verification. Consequently, certified plantations are permitted to expand into recently deforested land without penalty. The theoretical yields of 4G feedstocks (i.e. algae and synthetic biology) is 50-100 t oil/ha; however, current production levels are 5-10 times those of palm oil. This is why 1G feedstocks continue to be used in approximately 85% of global biofuel production. The feedstock hierarchy is not a linear progression; rather, it is a locked system where economic, infrastructural and regulatory barriers prevent transition despite environmental imperatives – reframing the central question from ‘which feedstock is best? or 'what systemic changes need to happen to allow for feedstock diversification?'.

As presented in Table 1, a comparison highlights a fundamental potential clash in the manufacturing biofuels. First generation (1G) feedstocks such as palm oil and soybean are well-established in agrotechnology and are known to be highly productive. However, their long-term sustainability is compromised by severe ecological costs including deforestation and loss of biodiversity, particularly in the case of land use change initiated plantation. Third generation (3G) options, such as the utilization of algae and used cooking oil (UCO), have the potential to facilitate the delinking of energy production from food security and land-use conflicts. However, the data demonstrated that these environmental benefits are currently outweighed by substantial techno-economic challenges, including high capital investments and logistical complexities.

Table 1. Classification of vegetable oil feedstocks

| Feedstock | Generation | Main Advantages | Main Sustainability Concerns |
|---|---|---|---|
| Palm oil | 1G | High yield, established supply chain | Deforestation, biodiversity loss, land-use change [35,36] |
| Soybean, rapeseed, sunflower oil | 1G | Globally traded, known agronomy | Competition with food, indirect land-use change [37] |
| *Jatropha curcas* | 2G (non-edible) | Growing on marginal/degraded land, low food competition [38] | Limited commercial scalability, variable oil content |
| Algae & micro-algae | 3G | Very high lipid productivity, can use wastewater [39] | High capital cost, water/energy demand |
| Genetically modified algal biomass | 4G | Notably having higher yield compared to conventional algae [40] | Infancy stage of technology |
| Used cooking oil (UCO) | 2G (waste) | Circular-economy, avoiding land use [36] | Collection logistics, feedstock quality variability |

Fourth generation (4G) biofuels, which focus on advanced technologies such as genetically engineered organisms and carbon capture integration, promise to further enhance sustainability by improving carbon sequestration and fuel efficiency. However, these innovations are still in the early stages of development and face significant technical and regulatory challenges. Consequently, the future of industry does not depend solely on the identification of new feedstocks; it also depends on the resolution of the scalability and extraction challenges that are impeding the adoption of 2G and advancement of 4G technologies towards commercial viability.

In a 2020 report by the Azapagic Group, several items were compared from 1G up to 3G biofuel sustainability performance, such as Global Warming Potential (GWP), water footprints effect, eutrophication, and biodiversity-related effects. In their study, the reduction of GWP is primarily associated with the three effects, which are characterized by their occurrence in the final three categories [41]. This phenomenon has increased the alertness of responsible biofuel producers. Moreover, considering the stringent environmental regulations, it is no longer permissible to sell non-sustainable biofuels without restriction [42,43].

A recent study by Kant's group (2025) has indicated that there is a necessity to discuss the sustainability of biofuels in a more comprehensive manner. This should include the cultivation, lipid extraction, harvesting, and solvent usage during initial pretreatment of biofuels[44]. In line with Azapagic's observations in 2020, each generation of biofuels exhibits unique advantages and limitations, except for the fourth generation, which was the subject of a study in 2025. The first and second generations are faced with the challenges of food competition and high costs. In contrast, the third and fourth generations offer sustainable solutions without competing with food resources. The fourth generation, which utilizes genetic engineering techniques, is distinguished as the most economically viable and environmentally efficient option. Nevertheless, it remains dependent upon ongoing technological advancements and policy support.

A recent study by Rial's in 2024 posits that the palm oil production in Malaysia and Indonesia exemplifies a disruption to environmental balances[45]. This study demonstrates that the elements of biodiversity loss and deforestation represent important aspects for negative environmental effects of 1G biofuel plantation provided that the plan is not managed effectively. Although not explicitly mentioned, the following tabulation can be used to summarize their finding (Table 2).

Table 2. Overall observed GWP reduction and key limitation of 1G up to 4G biofuel

| Generation | Overall Life Cycle of GWP | Key Limitation |
|---|---|---|
| 1G | Lowest reduction potential | LUC |
| 2G | Significant reduction | Mid-stage R&D |
| 3G | High reduction | Mid-stage R&D |
| 4G | Highest reduction | Early-stage R&D |

Table 2 summarizes the overall life cycle of Global Warming Potential (GWP) reduction across four generations of technology. It emphasizes the key limitations and reduction potential in each generation: 1G demonstrates the lowest reduction potential with land use change (LUC) as a key limitation; 2G and 3G technologies are in mid-stage research and development (R&D) with significant and high reduction potentials, respectively; 4G is at an early R&D stage and offers the highest reduction potential. First-generation biofuels from food crops (corn ethanol, sugarcane ethanol, rapeseed biodiesel, and palm biodiesel) exhibit heterogeneous life-cycle greenhouse-gas (GHG) performance that is highly sensitive to land-use change. For instance, corn ethanol can still yield about a 30% reduction in life-cycle GHGs relative to gasoline when land-use-change emissions are included [46]. Average first-generation savings can approach ~50% if indirect land-use change (LUC) is excluded [47]. However, the incorporation of realistic LUC scenarios for EU supply chains has been demonstrated to result in a reduction of savings to near-parity or even the generation of net increases (the reported ranges for simulated scenarios are from −2% to 13% savings); In one life cycle comparison, palm biodiesel has been reported to deliver very large direct GHG mitigation relative to fossil diesel (an 84% reduction in that study's comparison). Nevertheless, it should be noted that the results are case-sensitive to residue management and co-product treatments [48]. Specific $gCO_2$-eq per MJ values for individual first-generation routes (e.g. sugarcane ethanol, rapeseed biodiesel) are not consistently reported in the supplied corpus for every feedstock and thus cannot be stated here with confidence. Second-generation biofuels derived from lignocellulosic biomass and agricultural residues (e.g. cellulosic ethanol, switchgrass routes) are reported to offer greater GHG reduction potential than first-generation pathways. This is largely because they displace more fossil carbon per unit fuel and avoid competition with food crops competition but the sources provided do not provide consistent, comparable $gCO_2$-eq/MJ or single-number percentage reductions across pathways in the corpus available here. As a result, precise pathway-level metrics are not reproducible from the provided material [46,49]. Third-generation microalgae-based biofuels demonstrate substantial pathway dependence. Cradle-to-gate LCAs have reported 0.85–1.46 kg $CO_2$-eq per kg of algal-based biodiesel for specific cultivation and processing scenarios[50], while integrated process LCAs of high-productivity algal conversion report pathway-specific global-warming-potential results of 111.2 g $CO_2$-eq per MJ for a biochemical processing route and −2 g $CO_2$-eq per MJ for a thermal-chemical pathway under the study's assumptions. This illustrates that certain algal pathways can be near-carbon-neutral or net-negative at the fuel gate 6. Comparative studies also report very large percentage savings for microalgal biodiesel versus conventional diesel in some configurations (a ~95% direct GHG saving reported in one comparative assessment), However, it should be noted that such claims are strongly dependent on nutrient and energy inputs, wastewater usage, and conversion technology. The existing literature discusses fourth-generation approaches that couple engineered organisms, advanced biorefineries and explicit carbon-capture or bio-sequestration strategies. These are stated to have theoretical net-negative potential and to be the generation explicitly aimed at delivering negative emissions when $CO_2$ is captured and stored as part of fuel production. Nonetheless, the supplied corpus does not provide a consistent set of pathway-level, generalizable numerical values for fourth-generation routes to report here with confidence. Consequently, Life Cycle Assessment (LCA) data must exhibit a high degree of reliability.

## 3. Assessing the Environmental Footprint: Beyond Life Cycle Assessment (LCA)

For a more comprehensive assessment of the viability of selected biofuel feedstocks, a quantitative analysis is required that investigates deeper beyond simple oil yields and examines the overall environmental impact. In this section, the "Calculated LCA" is a well-accepted primary tool for auditing the potential impacts, with a focus on the net greenhouse gas (GHG) balance to identify any carbon debts that arise during cultivation until fuel production. This assessment also helps prevent shifting environmental burdens by carefully measuring trade-offs, such as deforestation, biodiversity loss, and the local pressures of intensive agriculture on water scarcity and soil health (eutrophication)[51]. This assessment is critical for identifying which feedstocks maintain their sustainability traits when subjected to LCA scrutiny.

### *3.1. GHG balance*

A critical review of the literature on GHG balance reveals not only the variability of the reported values but also a systemic methodological crisis enabling greenwashing at scale. The range of the carbon intensity of palm oil biodiesel is between −30 and +200 g $CO_2$-eq/MJ depending on whether land-use change (LUC) is included. This 230 g $CO_2$-eq/MJ range makes cross-study comparison meaningless and allows the cherry-picking of positive results[52]. The literature reports a narrow range of 40–60 g $CO_2$-eq/MJ (excluding LUC) that superficially meets the 65% GHG reduction threshold of the EU RED II. When LUC is included in the analysis, the carbon intensity of peatland conversion can exceed twice the baseline for fossil fuel, with a value more than 200 g $CO_2$-eq/MJ. The structural cause of this inconsistency is not technical but rather in governance-related factor, the ISO 14040/14044 standards provide general framework for LCA principles but do not mandate specific allocation methods, temporal boundaries or LUC accounting protocols. This can result in a 'race to the bottom' in which studies compete to report the most favorable results. This issue is further compounded by incentive misalignment, whereby industry-funded studies are significantly more likely to omit LUC data than independent academic studies. This is because deforestation data is commercially sensitive, and its inclusion typically reverses the apparent sustainability advantage of palm biodiesel. The consequence of this is a verification paradox: the more LCA studies are published, the more difficult it becomes to establish ground truth. This is due to methodological diversity allowing any stakeholder to find a study that supports their preferred conclusion. The resolution of this crisis requires the mandatory harmonization of LCA system boundaries and LUC accounting protocols - not as a technical refinement, but rather as a governance reform that removes the incentive to selectively omit unfavorable data.[53,54,55].

In 2020, Azapagic's group provided a summary of the number of LCA used for mapping the potential of biofuels and each trade as follows Table 3[41].

The tabulated data above clearly indicates that most studies prioritize Land Use Change (LUC) calculations for palm oil (46%), soybean (44%), and sugarcane (41%) plantations, far higher than compared to other crops. This high level of scrutiny confirms the scientific consensus that the sustainability of these feedstocks depends heavily on LUC contributions, particularly in the context of forests or peatland clearance for the initiation of plantation. Since such land conversion releases massive amounts of stored carbon, disregarding the release of carbon resulting from LUC renders it impossible to accurately assess its environmental impact. It is therefore widely considered that the issue of the 'carbon debt' from deforestation represents a critical consideration in the context of the viability of these tropical biofuel plantation.

A more recent comprehensive review by Osman et al. highlighted that the utilization of various biomass-to-energy conversion pathways (ranging from thermochemical processes, such as pyrolysis, to biological fermentation) is increasingly asserted upon examination through rigorous Life Cycle Assessment (LCA) methodologies[56]. These assessment results are essential for quantifying the specific environmental burdens associated with each stage of the supply chain, allowing for a precise evaluation of key metrics such as the net greenhouse gas (GHG) balance, acidification potential, and energy return on investment

(EROI) across a "cradle-to-grave" scope. This study emphasizes that in the absence of such standardized LCA frameworks, it is impracticable to accurately assess environmental burden shifting, where the mitigation of carbon emissions might inadvertently exacerbate other ecological impacts, such as land-use change (LUC) or water eutrophication. Consequently, the integration of proper LCA modelling is identified as a prerequisite for evidence-based policy decisions. This ensures that selected biofuel technologies deliver verifiable sustainability benefits over conventional fossil fuel systems. However, it should be noted that not all summarized studies have a direct relation to vegetable oil usage as feedstocks. A more detailed review is presented in Table 4 presents. It is interesting to note that, in contrast to the findings of the more recent review, there are very few LCA studies resulting from South Asian authors, even though the region is the largest producer of palm oil. A single published work from Purnama's group in 2025 comprehensively explores the impact of palm oil plantations on biodiversity, though it remains deficient in quantitative data for their LCA study results. A critical analysis of the current bibliometric landscape reveals a significant geographical asymmetry: despite the Asia-Pacific region - specifically Indonesia and Malaysia - being the primary players in global palm oil cultivation, there is a conspicuous scarcity of primary Life Cycle Assessment (LCA) studies led by researchers and institutions in neighboring production zones. This phenomenon presents a methodologically challenge, given its reliance on secondary Life Cycle Inventory (LCI) datasets derived from non-tropical contexts or global averages. The datasets frequently underrepresent the high spatial heterogeneity of emission factors associated with peat soil oxidation and palm oil mill effluent (POME) treatment, which are specific to the region [57]. Furthermore, the absence of locally generated empirical data compromises the accuracy of land-use change (LUC) modelling. This, in turn, forces global assessments to default to generalized satellite sensing and approximations[58,59]. This approach may not accurately distinguish between the conversion of high-conservation-value forests and the rehabilitation of degraded agricultural frontiers. Consequently, this research gap risks creating a policy environment governed by "consumer-market" perspectives that overlook site-specific agronomic realities and the verifiable mitigation potential of local smallholder management practices in the tropics.

Table 3. Overview of LCA studies for well-established biofuel types

| Fuel type/ feedstock | Location | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Europe | N. America | S. America | Asia | Africa | Australia | Without | With | Total |
| *Bioethanol-1st gen.* | | | | | | | | | |
| Corn | 6 | 23 | 0 | 1 | 0 | 0 | 16 | 14 | 30 |
| Molasses | 4 | 12 | 0 | 25 | 3 | 4 | 30 | 18 | 48 |
| Sugar beet | 19 | 1 | 0 | 0 | 1 | 0 | 14 | 7 | 21 |
| Sugarcane | 0 | 4 | 32 | 1 | 1 | 0 | 28 | 10 | 38 |
| Wheat | 39 | 0 | 0 | 0 | 0 | 0 | 28 | 11 | 39 |
| *Bioethanol-2nd gen.* | | | | | | | | | |
| Bagasse | 1 | 1 | 3 | 1 | 0 | 0 | 6 | 0 | 6 |
| Forest residue | 16 | 7 | 0 | 0 | 0 | 0 | 23 | 0 | 23 |
| Miscanthus | 14 | 9 | 0 | 0 | 0 | 0 | 16 | 7 | 23 |
| Short rotation coppice | 29 | 2 | 0 | 0 | 0 | 0 | 17 | 14 | 31 |
| Stover | 12 | 18 | 0 | 0 | 0 | 0 | 27 | 3 | 30 |
| Straw | 27 | 1 | 0 | 9 | 0 | 0 | 32 | 5 | 37 |
| Swith grass | 2 | 17 | 1 | 0 | 0 | 0 | 18 | 2 | 20 |
| *Biodiesel-1st gen.* | | | | | | | | | |
| Palm oil | 0 | 0 | 3 | 56 | 0 | 0 | 32 | 27 | 59 |
| Rapeseed | 19 | 13 | 2 | 0 | 4 | 0 | 24 | 14 | 38 |
| Soybean | 3 | 10 | 18 | 5 | 3 | 0 | 29 | 10 | 39 |
| Sunflower | 1 | 0 | 2 | 0 | 5 | 0 | 5 | 3 | 8 |
| *Biodiesel-2nd gen.* | | | | | | | | | |
| Camelina | 1 | 13 | 0 | 0 | 0 | 0 | 14 | 0 | 14 |
| Jatropha | 0 | 0 | 7 | 8 | 7 | 0 | 18 | 4 | 22 |
| UCO/Tallow | 17 | 1 | 3 | 5 | 1 | 0 | 27 | 0 | 27 |
| *Biodiesel-3rd gen.* | | | | | | | | | |
| Algae | 13 | 28 | 4 | 13 | 0 | 2 | 60 | 0 | 60 |
| Total | 223 | 160 | 75 | 124 | 25 | 6 | 464 | 149 | 613 |

Table 4. Summarized LCA studies for vegetable oil utilization as fuels [56]

| Ref | Region | Functional Unit | Feedstock | Process | Product | LCA tools | Database |
|---|---|---|---|---|---|---|---|
| [60] | India | Mass of $CO_2$ equivalent released per MJ of fuel produced | Microalgal biomass | Comparison of Transesterification ($Fe_2O_3$ catalyst with HCl catalyst) | Biodiesel | GaBi 7 | nm |
| [61] | nm | 1000 kg of biodiesel produced per day | Waste cooking oil | Transesterification (waste chicken eggshell derived CaO catalyst) | Biodiesel | openLCA 1.8 | Agribalyse and NEEDS |
| [62] | nm | 100,000 kg of dry algae biomass for 340 days of yearly operation | Microalgal biomass from *Chlorella vulgaris* | Lipid extraction followed by lipid recovery and transesterification | Biodiesel | nm | nm |
| [63] | nm | Mass of $CO_2$ equivalent released per MJ of fuel produced | Algae harvested from an algal turf scrubber | Comparison of Biochemical processing with Thermochemical processing | Biodiesel | nm | GREET |
| [64] | UK | 1 ton of spent coffee grounds treated | Spent coffee grounds | Comparison of Incineration, Landfilling, Anaerobic digestion, Composting followed by direct application to land | Biodiesel, compost | GaBi 8.7 | Ecoinvent 3.3 |
| [65] | Gulf region | 1000 kg of biodiesel | Waste date seeds | Esterification using a magnetic catalyst | Biodiesel | SimaPro | SimaPro LCA |
| [66] | Karnataka, India | Biomass achievable in 1 ha area | Microalgal biomass | Comparison of Acid catalysis Biocatalysis | Biodiesel | OpenLCA 1.10.3 | Ecoinvent 3.6 |
| [67] | Pakistan | 1000 kg of biodiesel | Waste loquat seeds | Transesterification using a $CaO/CeO_2$ catalyst | Biodiesel | SimaPro | SimaPro LCA |

nm : not mentioned

Table 5. Reported inconsistencies for LCA results of vegetable oil plantations

| Ref | Full title | Journal | Key methodological issues discussed |
|---|---|---|---|
| [68] | On quantifying sources of uncertainty in the carbon footprint of biofuels crop/feedstock, LCA modelling approach, land-use change, and GHG metrics | *Biofuel Research Journal* | The study identified the largest sources of variance in biofuel carbon footprints are feedstock selection, inclusion/exclusion of land-use change, and the LCA modelling approach (as opposed to the GHG metric); and recommended sensitivity analyses to reflect these choices. |
| [69] | Comparing sources and analysis of uncertainty in consequential and attributional life cycle assessment review of current practice and recommendations | *International Journal of Life Cycle Assessment* | The study reviewed recent LCA practice and identified the paucity of reporting of uncertainty, the study classified parameter/scenario/model uncertainty, and highlighted multi-functionality (allocation vs. substitution) as a major unresolved source of divergence between studies |
| [70] | Deforestation and greenhouse gas emissions could arise when replacing palm oil with other vegetable oils | *Science of The Total Environment* | The study demonstrated that differing assumptions about land-use change (direct and indirect) and allocation across oil crops produce large differences in estimated GHG outcomes, and stresses the sensitivity to LUC scenario choices and spatial assumptions |
| [71] | Certified palm oil reduces greenhouse gas emissions compared to non-certified | *Journal of Cleaner Production* | The study provided LCA comparison and reported data quality assessment and uncertainty analysis, noting that soil type (peat vs mineral) and data sourcing drive major differences between certified and non-certified results |
| [72] | Study of life cycle assessment in biodiesel production from crude palm oil and its benefits for the sustainability of oil palm industry in Aceh province Indonesia | *IOP Conference Series: Earth and Environmental Science* | The study recorded that multiple LCA studies of Indonesian biodiesel report inconsistent results and attribute divergence to data inconsistency and lack of field-representative data and reporting |

It is imperative to consider the consistency of the LCA results for each scenario of vegetable oil plantation. It has been posited that the variability of LCA reports is attributable to a range of factors, including different scopes, methodologies, and numbers of technical aspects as follows:

The inconsistencies documented in Table 5 are not merely methodological discrepancies; rather, they reflect a systemic pattern with direct policy consequences. The five factors driving variability – namely feedstock selection, LUC inclusion, allocation methods, soil and contextual data, and temporal scope - are not independent. Rather, they interact to produce outcomes that can differ by an order of magnitude for the similar feedstock. It is important to acknowledge that these are not random errors but rather directional biases. A systematic review of studies funded by stakeholders within palm oil industry reveals a consistent selection of methodological choices (excluding LUC, using economic allocation, and applying short temporal boundaries) that are designed to minimize reported carbon intensity. The result of this study is that the published LCA literature presents an artificially favorable picture of palm oil sustainability that does not withstand scrutiny when standardized methods are applied. The regulatory consequences of this are as follows: if the EU RED II compliance is to be assessed using industry-selected LCA studies, palm oil biodiesel appears to meet the 65% GHG reduction threshold; if the studies used for assessment include full LUC accounting for peatland conversion, it fails by a factor of three. The absence of mandatory standardization thus functions as a structural enabler of greenwashing, allowing policy compliance to be demonstrated on paper while environmental damage continues on the ground.

### *3.2. Deforestation caused by LUC*

The relationship between LUC-driven deforestation and biodiversity loss presents a fundamental efficiency paradox that the existing literature describes but rarely interrogates analytically. Palm oil has been demonstrated to yield 3.36 t/ha (compared to 0.4 t/ha for soy), which, in theory, should result in a reduction of total land requirements and thus minimize biodiversity impacts relative to competing oilseeds. However, the expansion of palm oil cultivation is a significant driver of disproportionate biodiversity loss precisely, owing to three mechanisms that are not effectively addressed by conventional land-use efficiency metrics. Firstly, the issue of geographic concentration is highly pertinent: 85% of palm oil production occurs in Indonesia and Malaysia, which contain 15% of global biodiversity hotspots. This means that each hectare converted carries far higher biodiversity cost compared to equivalent expansion in temperate soybean regions. Secondly, the conversion dynamics: the expansion of palm oil disproportionately focused on primary and secondary forests (accounting for approximately 60% of new plantations between 2000 and 2019) rather than already-degraded lands. This is because forest soils offer higher initial fertility level, creating a perverse incentive where the most biodiverse lands are also the most economically attractive for conversion. Thirdly, the issue of landscape fragmentation must be considered. even 'sustainable' certified plantations have been shown to create edge effects that degrade adjacent forest patches, with biodiversity impacts extending 1–2 km beyond the boundaries of plantation, meaning that the effective area of ecological disruption substantially exceeds the planted area. The carbon debt analysis reinforces this critique. The conversion of lowland tropical forest generates approximately 610 Mg $CO_2$/ha of carbon debt requiring 86 years to be repaid, while peatland conversion generates approximately 3,000 Mg $CO_2$/ha requiring 423 years – a period far in excess of the 20–30-year economic lifespan of typical plantations. This means that the majority of palm biodiesel produced from converted tropical land will not achieve net carbon benefits within any policy-relevant timeframe, fundamentally undermining the rationale for treating it as a climate solution.

In 2014, Liu et al. found that Land Use Change (LUC) for biofuel production was a primary driver of global biodiversity loss, posing a threat over 80% of the world's endangered bird, mammal, and amphibian species through habitat destruction and fragmentation[73]. This conversion frequently replaces complex ecosystems with monocultures that function as "green deserts" For instance, palm oil plantations support significantly fewer bird species than natural forests, favoring only common, eurytopic species with low conservation value. The scale of this transformation is substantial. In Brazil alone, it is estimated that the expansion of sugarcane and soybean plantations will result in the conversion of 12.2 million hectares of forest and 4.6 million hectares of other natural ecosystems by 2020. Beyond the loss of direct habitats, intensive management has been shown to degrade the remaining environment. For example, the cultivation of maize absorbs 41% of global herbicide use and 17% of pesticides, while causing soil erosion rates as high as 19.7 tons per acre in the USA. Furthermore, the introduction of genetically modified crops on a global scale has given to significant concerns regarding potential genetic risks. These risks include the evolution of glyphosate-resistant "superweeds" such as Amaranthus rudis and Conyza canadensis, which can invade and alter ecosystems. This phenomenon has been observed on an extensive scale, with these superweed having been identified on 174 million hectares of land globally.

In the chapter entitled “Recent Trends in Lignocellulosic Biofuels and Bioenergy, Land Use Change (LUC)” (Barwant et al. in 2025), it is asserted that biofuel expansion-driven activity is a primary cause for biodiversity loss, with impacts heavily dependent upon the specific feedstock and LUC scheme[74]. The conversion of natural habitats into monoculture has resulted in simplified ecosystems that function as "green deserts" compared to previous ones. For instance, palm oil plantations in Southeast Asia support approximately 85% fewer species than the primary forests they replace which is a drastically higher loss than the ~60% reduction in biodiversity observed in US corn and soybean fields relative to unconverted habitats. This severe disparity highlights that tropical feedstock, such as palm oil, which frequently displaces carbon-rich peatlands and rainforests, incurs far greater ecological costs than temperate crops. Furthermore, while first-generation crops such as maize and sugarcane often require intensive irrigation and agrochemicals, intensifying water disparity, and eutrophication, palm oil's unique threat lies in its massive "carbon debt" from deforestation, which can take over a century to repay. This effectively nullifies any short-term GHG savings compared to fossil fuels. Thus, while all large-scale monocultures reduce local biodiversity, quantitative evidence highlights that the conversion of tropical forests to palm oil plantations represents a disproportionately severe threat to global species richness and climate stability in comparison to other agricultural bioenergy pathways.

Another interesting study was recently published by Murphy et al. in 2025 (see Table 6)[37]. This present study constitutes a comprehensive comparative study of major vegetable oil sources. The following table summarizes their study.

Table 6. Summarized effect of vegetable oil plantation towards environment [37]

| Metric | Palm | Soybean | Rapeseed (Canola) | Sunflower |
|---|---|---|---|---|
| Crop type | Perennial (25-year lifecycle) | Annual (Replanted yearly) | Annual | Annual |
| Average oil yield | 3.3-3.36 tonnes/ha (highest) | 0.47-0.6 tonnes/ha (lowest) | 0.74 tonnes/ha | 0.78 tonnes/ha |
| Global Land use | ~29 million ha (low realite to output) | > 120 million ha (high relative to output) | ~ 35 million ha | ~25 million ha |
| Global production | >90 million tonnes | ~60 million tonnes (oil only) | ~26 million tonnes | ~20 million tonnes |
| Land efficiency ratio | 1x (baseline) | ~7x more land needed | ~4.5x more land needed | ~4.3x more land needed |
| Carbon footprint (best case) | ~2.37 tonnes $CO_2$ eq/ton oil (Mineral oil with biogas capture) | > Palm oil case (driven by land clearing & mechanization) | ~3.14 tonnes CO2 eq/ton oil (driven by Nitrogen fertilizer) | Moderate |
| Carbon footprint (worst case) | ~13.8 tonnes $CO_2$ eq/ton oil (peatland conversion) | High (Amazon/Cerrado deforestation) | Moderate | Moderate |
| Primary environmental | Peatland conversion (High biodiversity losses) | Rainforest deforestation | Eutrophication | Nutrient depletion |
| Key advantage | Highest oil output/ha land | High protein co-product | Also grows in sub-tropical region | Drought tolerant |

Their study reveals a fundamental trade-off between land use efficiency and biodiversity impact. Palm oil has been identified as the most productive crop, with an average yield of 3.36 tonnes of oil per hectare, approximately 4 to 7 times higher than that of its competitors (sunflower: 0.78 t/ha; rapeseed: 0.74 t/ha; soybean: ~0.47 t/ha). This efficiency is such that palm oil provides more than 35% of the world's vegetable oil needs, utilizing a land area of less than 6% of that allocated to oil crop cultivation. Soybeans, on the other hand, are a "land-hungry" crop, requiring vast areas (more than 120 million hectares globally) to produce the similar amount, leading to widespread deforestation in the Americas. However, the environmental benefits of palm oil's high yield are strictly conditional on location. The carbon footprint of palm oil produced on mineral soils has been shown to be similar to or even lower than that of European rapeseed oil (~2.37 tonnes $CO_2$ eq/t oil). By contrast, the conversion of tropical peatlands to plantations results in significant releases of stored carbon to the soil, thereby propelling emissions to unsustainable levels (approximately 13.8 tonnes $CO_2$eq/ton oil) and creating a "carbon debt" that requires over a century to be repaid. Annual crops such as rapeseed and sunflower have moderate and consistent environmental costs arising from the utilization of fertilizers and mechanization. Palm oil has a binary sustainability profile: it is the most land-efficient solution when managed responsibly, but the most ecologically damaging when it drives the conversion of peatlands. The environmental impact of palm oil cultivation is dependent on the local soil condition. Under optimal condition, the process can have positive impact on environment.

In the study by Hergoualc'h's group in 2020, the land use change of degraded forest into palm oil plantation in Brazil was observed to result in a substantial reduction in soil $N_2O$ emissions due to lower nitrogen inputs (from 213 to 84–168 kg N $ha^{-1}$ $y^{-1}$)[75]. This finding is in contrast to those reported in Sumatra, where similar N reductions did not affect emissions. Furthermore, there are reports of increased emissions in industrial plantations, presumably due to the higher level of fertilizer use. Importantly, none of the four studies on forest conversion accounted for emissions from frond piles, which cover 6–15% of plantations and supply significant nitrogen (~59 kg N $ha^{-1}$ $y^{-1}$) to the soil. Notwithstanding the finding of one study that frond piles contribute little to overall emissions, uncertainties in measurement methods highlight the necessity for further investigation. Therefore, in the end, robust LCA studies are required to support the sustainable palm oil plantation efforts.

### *3.3. Water and soil impact*

In this study, the impact on water and soil is examined separately to provide a more in-depth analysis of the circularity of vegetable oil plantations. As a comprehensive example, the Castanheira group has dissected the environmental effect of biodiesel development in Brazil as their intended area of study (Table 7)[76].

The investigation revealed that the environmental impact of Brazilian biodiesel on soil and water distribution is defined by the massive agroecological imbalance between its primary feedstocks. In this context, soybean (accounting for ~80% of production) imposes a significantly higher extensive burden than the intensive profile of palm oil. A low average oil yield of soybeans, estimated at approximately 0.5 tonnes per hectare, necessitates extensive land mobilization, leading to widespread soil compaction and erosion. The process demands enormous inputs of potassium (K) and phosphorus (P) fertilizers. The runoff from these nutrients is quantified as the leading contributor to freshwater eutrophication and terrestrial acidification in the lifecycle. In contrast, the yield of palm oil plantation from a single hectare of land is 4–6 tonnes, a tenfold increase in land-use efficiency. However, this increase in productivity has been shown to result in the creation of localized hotspots for nitrogen leaching and nutrient saturation if adequate measures are not taken to manage the use of cover crops. Furthermore, while the cultivation phase is predominantly rain-fed (thus, minimizing blue water extraction), the chemical intensity of soybean production involves high loads of herbicides (specifically glyphosate), creating a significant terrestrial ecotoxicity footprint that is in contrast to the lower agrochemical requirement of mature palm plantations. Thus, the water and soil sustainability of the sector is chemically constrained by a trade-off between the high fertilizer and pesticide load required to support the low-yielding soybean monocultures and the localized nutrient management challenges of high-yield palm expansion. One study by Lorensia's group highlighted the existence of apparent disputes between the European Union data for the green aspect in Palm Oil plantations against Indonesia data as the current highest palm oil producer[77]. Their findings are tabulated as follows Table 8.

Table 7. Localized environmental effect study for different bio-oil sources [76]

| Feature | Soybean Oil | Beef Tallow | Palm Oil |
|---|---|---|---|
| Status in Brazil | Dominant (primary feedstock ~ 80 % share) | Secondary (major supplement 15-20 % share) | Emerging (high potential in North/Amazon region) |
| Average yield | Low: ~ 0.5 ton oil/ha | N/A: waste product | Highest: 4-6 tonnes oil/ha |
| GHG emissions | 23.1-29.2 gCO$_2$eq/MJ(65-72% reduction compared to fossil dieel) | Generally lower than any crop product | Potential for lowest emission if grown on degraded land |
| Land use impact | High:"land hungry":requires vast expansion | Indirect: tied to cattle ranching land usage | Low: extremely land efficient |
| Carbon debt risk | Critical:converting rainforest to soybean plantation takes centuries to repay | Moderate: linked to deforestation for land clearing | Binary: sustainable on degraded land: disastrous if converts peatlands/rainforest |
| Energy Balance | Positive, but limitedly low agricultural output/ha | High, as no direct agricultural energy input | High, driven by superior energy output/ha |
| Key advantage | Established infrastructure | Waste valorization | Superior productivity |
| Primary challenge | Low oil content per seed; High risk of Indirect Land Use Change | Inelastic supply | Labor shortages; Transport logistic in remote area |

Table 8. Recorded disagreement between Europe Union and Indonesia policy maker[77]

| Conflicting aspect | European Union position (RED II Policy) | Indonesia position (Counter argument &diplomacy) |
|---|---|---|
| GHG emissions | High emissions: classified palm oil as having the highest Indirect Land use Change (ILUC) emissions 109 gCO$_2$e/MJ. Comparison: higher than soybean (94 gCO$_2$e/MJ), rapeseed (80 gCO$_2$e/MJ), and sunflower (79 gCO$_2$e/MJ) | Unfair calculation: argues that palm oil is treated discriminatorily compared to other vegetable oils despite its higher productivity.<br>Emphasizes that CPO emissions are managed through sustainable practice under ISPO |
| Land use efficiency | Focus on expansion risk: focuses on the "risk" of expansion into high-carbon stock land rather than yield efficiency. Clains 45 % of expansion (2008-2015) occurred on high-carbon stock land (peatlands/forests) | Superior yield: highlights superior productivity.<br>Compared to Soybean i.e. palm oil has 10 times higher yield/ha. |
| Global land footprint | Deforestation primary mover: identifying palm oil as a primary driver of deforestation warranting a phase-out | Minimal footprint. Palm oil utilizes only 17 million ha globally,<br>compared to 277 million ha used by other vegetables oils. |
| Sustainability standards | External regulation: implemented the Delegated Act (RED II) to limit high ILUC risk biofuels. Plans to phase out palm oil in biofuels by 2030 | National certification: promotes ISPO (Indonsia Sustainable Palm Oil) as a valid standard<br>for sustainability. Criticizes EU for not having same certification for rapeseed and<br>sunflower oils. |
| Socio-economic impact | Environmental prioritization: priorities of EU's "Green Deal" and renewable energy targets (32% by 2030) over trade impacts. | Livelihood security: stresses that palm oil industries support 19.5 million workers. |

Their study indicated that the trade dispute between the leading palm oil producer, Indonesia, and the European Union over the Renewable Energy Directive (RED) II, is based on a fundamental clash between environmental risk modelling and agricultural efficiency metrics. The EU's justification for the 2030 palm oil biofuels phase-out plan is rooted in the high Indirect Land Use Change (ILUC) emissions of \$109~gCO2e/MJ, a figure that significantly exceeds those of soybean or rapeseed oil. Additionally, it is notable that 45% of the expansion in palm oil production occurred on high-carbon stock land. To counter these claims, Indonesia utilizes data regarding the superior land-use efficiency, using commercial diplomacy. Palm oil is considered by Indonesia to be the most efficient oil crop in the world, yielding 4 tons per hectare compared with the 0.4 tons yielded by soybean oil. The replacement of palm oil would require exponentially more land than the current utilization of 17 million hectares. This is particularly pronounced when compared to the 277 million hectares allocated to the production of competing vegetable oils. Indonesia furthermore criticizes the EU policy, citing its discriminatory nature in relation to the absence of any requirement for the Indonesia Sustainable Palm Oil (ISPO) certification despite the imposition of similar sustainability standards on European vegetable oils. Indonesia claims that such actions unfairly jeopardizes the livelihoods of 19.5 million workers in the name of environmental protection.

Regarding a more technical insight, one study has been well presented by Purnama et al. in their recent publication[36]. Their findings, particularly regarding the affected soil and water, are tabulated as follows Table 9.

Table 9. Recorded effect on soil and water due to the presence of palm oil plantation[36]

| Resource | Impact category | Specific effect & mechanism |
|---|---|---|
| Water | Depletion (Quantity) | Significant water consumption: intensive irrigation for palm oil plantation leads to the depletion of local water tables, affecting both drinking water and other water usage. Drying streams: expansion has been linked to stream drying up during dry seasons |
| | Pollution (Quality) | Chemical runoff: the leaching of chemical fertilizers (Nitrogen/Phosphorous) causes eutrophication. Toxicity: the presence of hazardous pesticide contaminates water sources. |
| | Cycle Disruption | Risk of flooding: reduced capacity of soil to infiltrate water results in increased surface runoff, and more frequent flooding and landslides. |
| Soil | Physical degradation | Compaction: heavy machinery and plantation design compact the soil, preventing rainwater from being absorbed into groundwater. Erosion: clearing vegetation for plantations, particularly on slopes, removes the fertile topsoils. |
| | Chemical degradation | Acidification: significant decrease of pH level of soil reduces suitability for the growth of other plantations and it requires higher level of chemical fertilizer inputs to maintain yields. |
| | Peatland damage | Carbon release: draining peatlands releases a significant amount of stored carbon for drained peats up to 50 times more $CO_2$ than the intact ones. |

Their study observed that the large-scale expansion of palm oil plantations puts significant pressure on soil and water ecosystems due to intensive agriculture and land conversion. A significant challenge is the requirement for substantial quantities of water, necessitating the implementation of extensive irrigation systems. This frequently results in the depletion of local freshwater sources, causing streams to run dry during the dry season. This then can lead to disputes over water usage for both local communities and other food crops. Conversely, during the rainy season, soil compaction in plantations limits infiltration capacity and groundwater recharge, leading to an increased frequency of local flooding. Furthermore, the process of erosion and acidification contributes to the degradation of soil health. This is particularly evident in areas of slopes or drained peatlands, where the soil undergoes degradation, resulting in a loss of its fertility, thereby necessitating a reliance on chemical inputs. This cycle is further complicated by chemical pollution. Runoff from fertilizers (nitrogen and phosphorus) and hazardous pesticides such as paraquat results in the leaching of these substances into water bodies, later leading to eutrophication, creating aquatic “dead zones” devoid of oxy-gen and contaminating sources of drinking water.

## 4. Policy Landscape & Governance Gaps (greenwashing vs. responsible plantation)

The policy landscape of palm oil sustainability is better described as a systemic credibility crisis than a 'division' between EU risk-orientation and Indonesian efficiency-focus, driven by three structural failures that explain why decades of certification initiatives have not reduced de-forestation. The first failure is outcome-blindness in certification design: The 'no deforestation' commitment as set out by RSPO is applicable exclusively to plantations established after 2005. This stipulation means that certified producers are at an advantage, given that they can claim sustainability credentials despite deforestation which occurred prior to the stipulated date. RSPO audits are conducted by third-party certifiers, financially remunerated by producers themselves. This then creates conflicts of interest, resulting in the adoption of more lenient interpretations. Satellite analysis reveals that approximately 30% of ISPO-certified plantations in Indonesia were established on recently deforested land between 2015 and 2020, thereby underscoring that the certification requirement has failed to prevent the practices it was designed to stop. The second failure is regulatory fragmentation: RSPO, ISPO, MSPO and EU RED II create a forum-shopping environment, where producers can select the least demanding standard, and where compliance with one scheme does not equal compliance with other schemes. The EU’s initiative to phase out palm oil biofuels by 2030 under RED II is an attempt to address this failure of certification mechanism. Nevertheless, this move has the potential to create a leakage problem, as it allows palm oil to be removed from EU markets and directed to non-EU markets without the adherence to sustainability criteria, without net reduction in global deforestation. Thirdly, the collapse of enforcement: only 15% of palm oil can be traced to specific plantations, with the remaining 85% left unverifiable for sustainability claims. Certification audits are conducted at intervals ranging from one to three years; however, deforestation can occur in weeks. The sanctions imposed for non-compliance are inadequate in terms of deterring violations. Collectively, these structural failures demonstrate that voluntary certification has become a marketing tool rather than an environmental safeguard. This is a verification paradox in which the proliferation of sustainability standards makes real verification more complex [78,79].

The following draft of the opening sub-chapter, based on the documents provided, first juxtaposes the contrasting claims of the EU and Indonesia, and then introduces “greenwashing” as an important lens through which to examine the gap between sustainability rhetoric and actual practices. In response, the

Indonesian government has dismissed the allegations, claiming that palm oil is subject to trade barriers that are not equally applied to other products, and therefore should not be regarded as a significant environmental threat. The Indonesian argument is based on agricultural efficiency. Palm oil is considered to be the most productive vegetable oil crop in the world, with a yield of approximately 3-4 tons per hectare, which is almost 10 times the productivity of soybean oil (0.4 tons/ha). The Indonesian representatives argue that the global land use for palm oil is relatively small (17 million hectares) compared to the 277 million hectares required for other vegetable oils. Consequently, a prohibition would ironically require an increased area of land to satisfy global oil demands. In addition, Indonesia demonstrates its commitment to domestic sustainability standards through the certification of Indonesia Sustainable Palm Oil (ISPO), which is presented as proof that the sector is compliance with environment management practices. In this dichotomy of "discriminatory regulation" and "sustainable production", the concept of greenwashing becomes inevitably implicated in the debate. Indonesia has been pushing ISPO, with the industry incorporating voluntary standards such as the Roundtable on Sustainable Palm Oil (RSPO) as a means of demonstrating environmental responsibility. However, critical reviews have exposed a disconnection between these 'sustainable' labels and reality on the ground. Research findings indicate that, despite the number of certifications, there are still significant gaps in the enforcement of these standards, with "certified" areas frequently resulting in the displacement of threatened habitat and the degradation of carbon-rich peatlands. In this sense, greenwashing is not only a corporate green marketing tool, but also a systemic one. Certification schemes, under the guise of "sustainability" as labelled by the EU, can perpetuate the ecological trade-offs of peatland subsidence and biodiversity loss.

Table 10. Greenwashing aspect studies and each finding:

| Ref | Title | Year | Greenwashing Aspects Identified | Key Findings |
|---|---|---|---|---|
| [80] | *Integrasi Hukum Ekonomi Lingkungan dalam Pembangunan Berkelanjutan: Analisis Praktik Greenwashing Industri Perkebunan Kelapa Sawit di Indonesia* | 2025 | Exaggerated sustainability claims<br>Lack of transparency in CSR reporting<br>No real reduction of environmental or social impact | Greenwashing is utilized to mask environmental degradation and poor corporate responsibility. |
| [81] | *Greenwashing dan Derajat Transparansi pada sektor Industri Ekstraktif di Jawa Timur dan Jawa Barat* | 2025 | Low transparency in environmental reporting<br>Misrepresentation of sustainability efforts | Greenwashing is widespread in palm oil plantations due to weak governance and lack of accountability. |
| [82] | *Evaluasi Sustainability Report Pada Perusahaan Minyak Kelapa Sawit Dalam Mempromosikan Sustainable Palm Oil* | 2020 | Misleading sustainability reports<br>Lack of third-party verification | Sustainability reports frequently omit key environmental and social data, indicating greenwashing. |
| [83] | *Ekspansi Kelapa Sawit di Asia Tenggara* | 2011 | Environmental degradation masked as sustainable development<br>Deforestation disguised as land use efficiency | Greenwashing is utilized to justify deforestation and land conversion. |
| [84] | *Model Kebijakan Hukum Tanggung Jawab Sosial Dan Lingkungan Perusahaan Dalam Mendukung Pembangunan Berkelanjutan* | 2023 | Greenwashing in CSR and sustainability claims<br>Lack of legal enforcement | Legal frameworks are weak, thus enabling companies to engage in greenwashing without facing any consequences. |
| [85] | *Tepung Mangrove: Inovasi Pangan Lokal untuk Ketahanan Pangan dan Pelestarian Lingkungan* | 2025 | Critique of greenwashing in palm oil industry<br>Promotion of sustainable alternatives | Greenwashing undermines authentic sustainability efforts. However, the utilization of alternatives products such as mangrove-based products offer solutions. |
| [86] | *Konservasi Hutan di Era Antroposen* | 2025 | Greenwashing in conservation claims<br>Weak enforcement of environmental laws | Greenwashing is utilized to justify continued deforestation and poor conservation practices. |
| [87] | *Green Marketing* | 2024 | Misleading marketing of sustainable palm oil<br>Lack of real environmental impact reduction | Greenwashing is a marketing strategy to appear eco-friendly without any actual environmental action being taken. |

The data, as presented in Table 10, represents a consistent pattern of greenwashing across various studies on vegetable oil plantations, particularly in the palm oil industry. These publications demonstrate that greenwashing is frequently employed as a tactical marketing and public relations tool, with the objective of creating a false sense of environmental and social responsibility among consumers. For instance, a substantial amount of research has demonstrated a frequent utilization of sustainability reports and CSR initiatives as instruments to hide the environmental damage from large-scale palm oil plantations including deforestation, habitat destruction, and substandard working conditions. These reports are seldom subjected to third-party verification and are characterized by lack of transparency and measurability. This makes it difficult to determine what companies' sustainability claims deliver. All these works deal with the gap between the statement of companies and their actual practices. It has been posited that the practice of "greenwashing" on the part of companies is to avoid government scrutiny and to protect their image without really changing their practices.

Furthermore, the data indicates a systematic pattern of greenwashing in the vegetable oil market, particularly in Indonesia and Southeast Asia. Several studies have identified inadequate legal frameworks, ineffectiveness of enforcement mechanism and lack of accountability as the underlying causes of the persistence of greenwashing. It is often the case that companies claim to be environmentally responsible, yet they frequently engage in selective reporting and the presentation of false indicators of sustainability. Moreover, they ignore the wider environmental and social impacts of their business activities. Some studies also suggest that to combat greenwashing, alternative sustainable approaches such as those based on mangrove agriculture are being promoted as authentic solutions. These alternatives offer openness, accountability and community engagement, factors that are typically absent from the palm oil sector. The findings suggest that, despite the widespread practice of greenwashing, there is an increasing awareness within academic circles and the general public of the necessity for increased regulation measures, independent auditing processes and transparency in reporting to underpin claims regarding sustainability with real environmental and social impacts.

## 5. Mitigation Strategies & Emerging Technologies

A critical evaluation of mitigation pathways reveals a trilemma between environmental performance, economic viability, and scalability that is obscured by descriptive listings of technological options. UCO valorization offers the highest reduction in GHG per unit of feedstock, with a 93% reduction in carbon intensity in comparison to conventional jet fuel and no LUC impacts. Additionally, it is compatible with existing refinery infrastructure as a drop-in fuel[88]. However, the scalability of the system is fundamentally constrained: even if global collection rates were to be doubled from the current ~ 4 billion gallons per year up to 10 billion gallons per year by 2030 [89,90], UCO theoretically could supply only 5–10% of global demand for aviation fuel. Furthermore, the collection and processing of palm oil results in the emission of more than 8 kg $CO_2$-eq/kg of oil. It is therefore important that careful accounting is employed to ensure a net environmental benefit[91]. Therefore, UCO is classified as a high-impact, low-volume solution and its optimal prioritization is for sectors that are hard to decarbonize such as the aviation and marine industries, as opposed to its utilization as a universal palm oil substitute. Marginal land strategies (castor, jatropha) have been shown to avoid the impacts of LUC and offer significant emission reductions (67.2% for castor on degraded soils). However, these strategies face agronomic barriers: castor yields on marginal lands (0.3–1.0 t/ha) are 3–6 times lower than palm oil on prime land, requiring proportionally more area for equivalent oil production. This negates the 'no LUC' advantage if marginal land cultivation displaces smallholder agriculture[92]. Coprocessing palm oil with fossil crude offers economic advantages through its compatibility with existing refinery infrastructure. Nevertheless, the environmental benefits are minimal. A blend of approximately 10 % vegetable oil in fossil diesel reduces GHG emissions by no more than 10 % compared to standalone fossil diesel when LUC is considered. This falls far below the 58% reduction required by EU RED II, classifying it as a transitional technology rather than a genuine sustainability solution[93]. The trade-offs demonstrate that no single pathway can replace palm oil on a large scale. An effective mitigation strategy must sequence interventions. These should include the immediate deployment of UCO for high-value applications, the scaling of marginal land strategies where spatial planning can guarantee genuine additionality, and the investment in advanced feedstock R&D (e.g. algae, synthetic biology) for long-term transition. It is also imperative to avoid the trap of treating any single technology as a comprehensive solution.

As summarized in Table 11, there are multiple alternatives of the direct utilization of palm oil as a fresh bio feedstock to produce biofuel and chemicals. In 2020, Patel's group provided a critical assessment of oleaginous microorganisms defined by their capacity to accumulate lipids exceeding 20% w/w of cell dry weight. These microorganisms were identified as dual-purpose feedstocks for both third-generation biodiesel and high-value nutraceuticals[112]. The review points out the high metabolic plasticity of some strains, whereby the synthesis of fatty acid can range from short (C6) to long hydrocarbon chains (C36), depending on the carbon source and cultivation conditions. The authors present a quantitative analysis of lipid yields in yeast strains including *Cryptococcus curvatus*, which exhibit lipid contents up to 70% w/w on waste cooking oil and 53% w/w on glucose, underscoring their capacity for cost-effective waste valorization. Thraustochytrids are recognized as leading producers of polyunsaturated fatty acids (PUFAs) particularly in the context of omega-3 production. The *Aurantiochytrium sp*. docosahexaenoic acid (DHA) concentration of 27.9 % of total lipids was observed when grown on glucose. In contrast, the *Schizochytrium limacinum* SR 21 produced 18.38 % DHA on glycerol. The review also discusses the metabolic trade-offs in the lipid accumulation. For instance, *C. curvatus* can accumulate up to 68 % w/w of its intracellular total sugars under nitrogen-limited conditions prior to redirecting flux towards lipid synthesis. This emphasizes the significance of proper metabolic engineering and cautious nutrient limitation strategies to optimize industrial yields.

Table 11. Tabulated key benefits of new technological alternatives

| Strategy | Product Focus | Key Benefits | Ref |
|---|---|---|---|
| Microbial oils (algae, yeast, fungi) | Biodiesel, food oils, nutraceuticals | No land use change, high yield, tailored profiles | [94,95] |
| Engineered Camelina | Biofuels, food, industrial oils | High yield, dual use, low environmental impact | [96] |
| Microbial Omega-3 Fatty Acids | Nutraceuticals, food additives | No overfishing, land use neutrality | [97] |
| Integrated Biorefineries | Biodiesel, chemicals, bioplastics | Waste valorization, reduced emissions | [98–103] |
| Tailored Oil Profiles | Food, industrial applications | Customizable, reduces need for palm oil | [104] |
| Waste-to-Oil Technologies | Biofuels, chemicals | Waste reduction, land use neutrality | [105,106] |
| Upcycling Used Oils | Biodiesel, lubricants, biofuel | Waste reduction, reduced demand | [107,108] |
| Oleochemicals from microbial oils | Surfactants, lubricants | Petrochemical replacement | [109] |
| Blending microbial oils | Food and industrial products | Gradual transition, reduced environmental burden | [110,111] |

A further study by a group of Barbieri has provided a comprehensive analysis of the extraction of microbe oil[113]. This study provides a strong case for the incorporation of fungal biotechnology into oil extraction processes. The findings demonstrate that the pretreatment of oilseeds with enzymes can significantly surpass conventional methods by breaking down the persistent lignocellulosic matrix that hinders the accumulation of intracellular lipids. The authors highlight several fungal genera, most notably *Aspergillus, Trichoderma*, and *Rhizopus* that are responsible for the production of tailored blends of hydrolytic enzymes (cellulases, hemicelluloses, and pectinases). It has been reported that these enzymes can effectively weaken the integrity of cell-wall, thereby facilitating the access of solvents or mechanical pressure to oil bodies. The authors discuss how specific fungal genera—notably *Aspergillus, Trichoderma, and Rhizopus*—secrete tailored cocktails of hydrolytic enzymes (cellulases, hemicellulases, and pectinases) that degrade cell wall integrity, thereby enhancing the accessibility of solvents or mechanical pressure to oil bodies. Quantitatively, the review cites research demonstrating that aqueous enzymatic extraction (AEE) using these fungal metabolites yielded oil recovery rates comparable to those attained by hexane-based processes, while also preserving heat-sensitive bioactive compounds. Moreover, the utilization of solid-state fermentation (SSF) with strains such as *Rhizopus oryzae* on palm kernels and *Fusarium oxysporum* on sunflower seeds has been shown to facilitate lipid release. Also, this process has been shown to reduce free fatty acid (FFA) levels, thereby improving the oxidative stability and overall quality of the oil. These findings suggest that a transition from chemical to biological extraction offers dual benefits, including a measurable reduction in the environmental impact of solvent use and a statistically significant increase in the yield of high-quality, antioxidant-rich vegetable oils. The data confirms that microorganisms have become a practical solution for the modern oil industry. It is evident that microbes can serve two roles. Firstly, they can be cultivated to produce oil directly, with yields reaching as high as 70 %. Secondly, they can act as tools to break down tough plant seeds, facilitating the oil release process. This evidence clearly explains that biological methods have become a feasible, efficient, and scalable alternative to conventional chemical processes. Another viable strategy is to utilize mix culture that enables $CO_2$ capture.

In 2022, the Dias group conducted a study on the valorization of primary brewery wastewater (PBWW) as a low-cost substrate for lipid production. The study compared the performance of the oleaginous yeast *Rhodosporidium toruloides* and the microalga *Tetradesmus obliquus* in both axenic and co-culture systems.[114] The study revealed a critical quantitative finding exhibiting the inability of *R. toruloides* to survive in monoculture within the raw effluent, likely due to the toxicity of organic acids. However, the establishment of a mixed consortium proved transformative, with the microalgae effectively detoxifying the medium to sustain yeast viability at approximately 99%. The study further demonstrated that nutrient management is essential for maximizing yield, as the mixed culture supplemented with 100 g/L of sugarcane molasses and urea achieved a peak lipid content of 26.3% w/w. These results underscore the industrial viability of symbiotic yeast-microalgae systems, which not only overcome the toxicity barriers inherent in waste effluents but also convert them into competitive lipid feedstocks for biodiesel production[115].

A further practical approach is to utilize co-processing scenario to enable biofuel derived from vegetable oil plantation to be utilized immediately to satisfy market demands. In 2020, the Hafyan group demonstrated, through multi-objective optimization, that the most viable configuration for an Empty Fruit Bunch (EFB) biorefinery operates at a maximum feedstock capacity of 100 ton/h. This configuration has been shown to yield an annual profit of $932 million USD while incurring a Global Warming Potential (GWP) of 284 tonnes $CO_2$-eq[116]. The optimal design resulted in a Fire and Explosion Damage Index (FEDI) of 595 and a Toxicity Damage Index (TDI) of 957 in terms of safety metrics. The plant's projected production capacity was expected to have a significant impact on the global market; representing 55% of the global demand for xylitol, 98% of demand for levulinic acid, 25% of demand for succinic acid, 90% of demand for guaiacol and 12% of demand for vanillin. The results obtained from the experiment were as follows: 10% of the glucose stream was allocated to the production of levulinic acid (with the remaining to succinic acid) and 70% of the lignin stream was allocated to the production of guaiacol (with the remaining to vanillin). The final selection of this configuration was performed by means of a Fuzzy Analytical Hierarchy Process (FAHP) where the eco-nomic performance was assigned a weight of 0.5, followed by safety with 0.3 and environmental impact with 0.2. The research group of Professor Shuhaimi Mahadzir (Universiti Teknologi PETRONAS) is leading this study, which is based on a strategic context in Malaysia, the second largest palm oil producer in the world, where such high-volume waste valorization is critical.[117]. This research provides a definitive economic argument for the transition from linear palm oil processing to a circular bioeconomy, proving that integrated biorefineries have the potential to transform regional agricultural liabilities into lucrative, globally competitive assets. In more conventional approach, the biofuel can be co-produced in conventional petroleum refining process. Bezergianni's group has published its finding on the utilization of conventional catalyst (CoMo and NiMo) in a coprocessing scheme for hydrotreating of waste cooking oil and heavy atmospheric gas oil[118]. The report indicates that the utilization of used cooking oil has no different effect on the NiMo catalyst, while the CoMo catalyst is found to be significantly impacted. This phenomenon is closely related to the rate of CoMo deactivation reaction in the presence of lipid co-reactant. Therefore, the findings of the present study demonstrate Ni-based transition metal catalysts are the most effective for the removal of oxygen from lipids. Their result of this study has provided valuable insights into the feasibility of utilizing existing refinery reactors as hydrotreating reactors for vegetable oil.

Similarly, in most cases, a review by Fu et al. in 2025 stated that, despite the challenges arising from strict aviation fuel standards, such as ASTM D1655, co-hydro processing vegetable oil with Heavy Atmospheric Gas Oil (HAGO) offers a viable route for the integration of biomass into fuels. However, this process requires meticulous catalyst selection. Studies have demonstrated that nickel-molybdenum (NiMo) catalysts exhibit superior performance in comparison to cobalt-molybdenum (CoMo) catalysts. NiMo catalysts demonstrate stability and heteroatom removal efficiency (HDS/HDN) despite the presence of oxygenates, whereas CoMo catalysts are subjected to inhibition and rapid deactivation. Although the addition of vegetable oil has been shown to improve diesel selectivity and saturation, the process must also be capable of managing the significant exothermic heat generated from deoxygenation reactions[102]. In a review published in 2024, Marquez et al. concluded that at least five regions have a significant impact on the utilization of vegetable oil-derived biofuel [101]. These regions, including the US, Brazil, India, Indonesia, and the EU, are known for either their abundant supplies of vegetable oil or technological prowess. In their review, most biofuel market leaders introduced vegetable oil as a blending agent for initial market acceptance; thus, resulting in an eventual increase in the blended amount on annual basis. This strategy once again signifies the effectiveness of the coprocessing scheme.

Nevertheless, any development from a product focal point of view must be supported by its actual effects on overall sustainability. The work of Seber et al. in 2022 revealed that even with different plantation origins, hydrogen sources, and processing schemes, most GHG traces originated from both fertilizers used in farming and energy utilization[119]. In a 2025 review, Velickovic conducted an accurate quantitative assessment of the sustainability of castor-based biofuel, emphasizing that environmental viability is contingent upon advanced lifecycle management and biorefinery integration[120]. Life Cycle Assessment (LCA) data revealed that substituting fossil jet fuel with castor-based alternatives led to a reduction in environmental impacts ranging from 36 to 85%, with castor-HEFA bio-jet fuel exhibiting lifecycle greenhouse gas emissions ranging from 41 to 78 g $CO_2$ eq/MJ, which is significantly lower than fossil baselines. Furthermore, the cultivation phase offers substantial carbon savings, with a notable a 67.2% emission reduction when converting grassland. Moreover, a biorefinery approach co-producing biomethane can further result in a reduction in emissions of 16%. However, the validity of their insights regarding the impact of LUC is yet to be proven, thus making their in-depth review potentially useful for the conversion of marginal or deserted land to vegetable oil plantations. Another study that made a significant impact was published by Rosmeika et al. in 2025[121]. Their cradle-to-gate life cycle assessment provided critical insights into the environmental effects of palm oil plantations towards environment in Sumatra, the largest palm oil producer in Indonesia. Resembling the findings in preceding studies, all negative environmental effects, such as GHG emissions, eutrophication, acidification, ozone layer depletion, and marine ecotoxicology, are predominantly attributable to monoculture plantations, even though their conclusion is focused on the impact of Palm Oil purity on GHG emissions.

As previously discussed, from, the apparent major negative impacts of vegetable oil plantations are frequently found in the plantation stage. This phenomenon can be attributable to a change in land usage that leads to deforestation or monoculture plantation. A viable strategy to increase productivity is through high-density or super-high-density plantations, as reported by Gennaro et al. (2012)[122]. In their report, high-density and super-high-density olive oil plantations have been compared as follows Fig. 1.

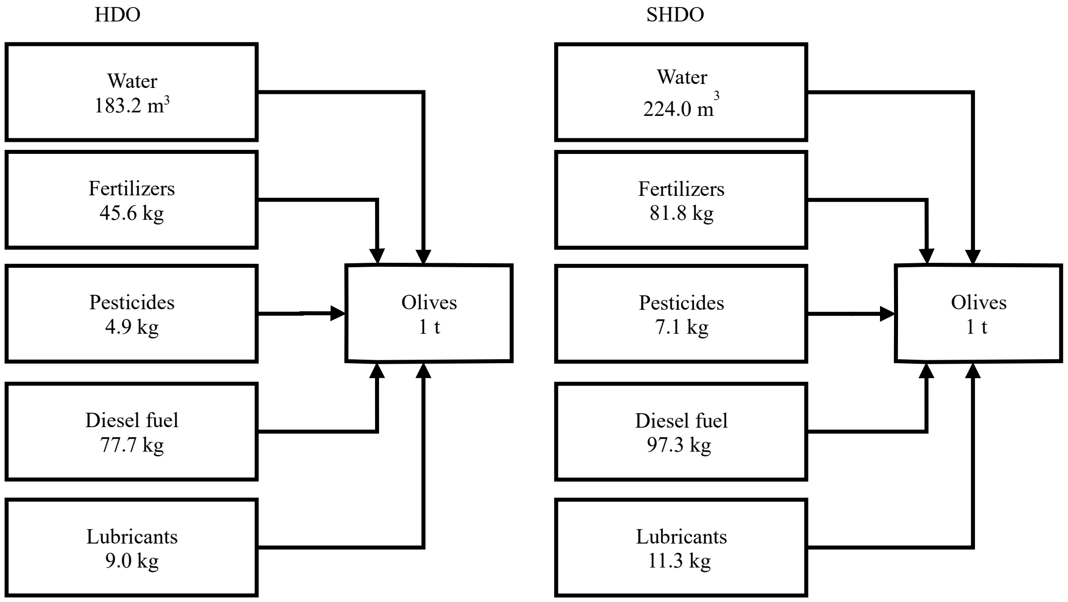

Fig. 1. Flow chart comparison for both High and Super high density olive oil plantation material balances (*HDO : High Density Olive; SHDO: Super High-Density Olive) [122]

From their work, it can be inferred that the increase in plantation density does not always enhance plantation efficiency in terms of mass balance. Unsurprisingly, given the more intensive monoculture plantation support, super high-density olive oil plantations have been identified as having the worst environmental effects in all selected LCA study aspects, including abiotic depletion, acidification, eutrophication, global warming potential, ozone layer depletion, human toxicity, aqua ecotoxicity, and terrestrial ecotoxicity. An in-depth review by Azhar et al. has tabulated several strategies for improving the sustainability of palm oil plantations as outlined in the following tabulated summary (see Table 12)[123].

Table 12. Tabulated Biodiversity-friendly approaches [123]

| Biodiversity-friendly practice | Justifications |
|---|---|
| Maintenance of forest patches and riparian corridors | The preservation of natural forest patches and riparian corridors within palm oil production landscapes is a landscape-level management measure that may enhance biodiversity conservation. |
| Maintenance of natural understorey vegetation | The maintenance of structural complexity within plantations can fulfil the production of highly demanded commodities and the conservation of biodiversity in productive landscapes. |
| Prohibition of hunting | Law enforcement should be implemented in conjunction with educational programs designated to educate oil-palm workers about biodiversity conservation and environmental regulations. |
| Control of introduced predators | The presence of Feral dogs has been observed to have a detrimental effect on both native fauna and animal livestock in palm oil plantations because of infrequent control from plantation management. |
| Adoption of biological control methods | The utilization of insecticides and herbicides has been proven to be ineffective as these chemicals promote pest resistance and eliminate beneficial insects such as pollinators and predators. Predatory insects and barn owls are excellent biological control for pests. |
| Application of tree-based enrichment | The implementation of tree-based enrichment measures within intensively managed palm oil plantations can increase bird species richness or bird abundance at relatively low cost. |
| Adoption of polyculture systems | Polyculture farming has been shown to have positive effects on the abundance and species richness of bats in palm oil production landscapes. |
| Minimization of wildlife roadkills | To reduce wildlife road accidents, it is recommended that appropriate road signs and speed bumps be installed in roadway within palm oil-cultivation areas. |
| Utilization of zero-burning technique | The technique is a practice of land clearing whereby an old area of plantation crops such as palm oil is felled, shredded, stacked and left in situ to decompose naturally. |
| Establishment of multiple stand age classes of palm oil | This measure has potential to enhance the structural complexity of palm oil plantations, thereby providing habitats for a variety of species. |
| Maintenance of water quality in palm oil waterways | The conservation of waterbirds requires the protection of intact wetlands supported by better management of drainage channels in palm oil production landscapes. |
| Employment of empty fruit bunch (EFB) methods along the sides of harvesting paths | The application of EFB plays an essential role in the enhancement of soil ecosystem functioning in palm oil plantations. |

The majority of tabulated approaches account for established palm oil plantations. In contrast, land remediation and prevention of Land Usage Change have scarcely been studied. Nevertheless, it is a fact that concurrently vegetable oil plantations are the sole viable sustainable fuel substitutes. Thus, it can be posited that the introduction of circularity could serve as a viable solution to prevent the overconsumption of fresh palm oil. In many cases, the introduction of waste cooking oil has been proven to be a plausible solution for the mitigation of deforestation resulting from land use change[124]. The impact of used cooking oil (UCO) on the environment was studied by Kumar et al. in 2025[125]. Upcycling used cooking oil (UCO) significantly contributes to both climate and land stability, offering a practical solution to both emission reduction and waste management. The impact on greenhouse gases is important: UCO-based bio-jet fuel has a carbon intensity that is 63.7% lower than standard jet fuel, and coprocessing UCO with fossil feedstocks reduces emissions by 7.7% compared to conventional diesel. As the conversion process itself generates 607.6 kg of $CO_2$ equivalent per ton, of which 68% is due to chemical reactions, localizing production has the potential to compensate for this by reducing the overall environmental impact by 30–50%. In addition, the practice of upcycling is of significance for land protection as improper disposal poses a is physical hazard. The addition of mere 5-10% waste oil into soil has been demonstrated to result in a substantial reduction in its shear strength, leading to foundation failures. Upcycling has the potential to transform a potential environmental hazard into a sustainable resource, rerouting huge waste streams (e.g. 1 billion pounds of waste generated annually in the US) into the fuel supply, thus promoting a circular economy and reducing fossil resource depletion by 34%.

## 6. Knowledge Gaps & Future Research Directions

The knowledge gaps in palm oil biofuel sustainability are not arbitrary research frontiers but rather reflect strategic ambiguity that benefits incumbent producers by obscuring environmental impacts and delaying regulatory action. Three categories of gaps can be distinguished by the type of barrier preventing their closure. The ISO standards are voluntary, and such do not include enforcement mechanisms. This has led to methodological gaps, such as the absence of standardized LCA protocols with obligatory LUC accounting. There is a need for international coordination to develop mandatory standards, which is opposed by palm oil producing countries, who are opposed to the disclosure of LUC impacts through standardization, a practice which is currently hidden by the flexibility in methodology. Deforestation data is commercially sensitive, with the result that there are still data gaps, including the inability to trace 85% of palm oil to specific plantations. Satellite monitoring technology exists (e.g. Global Forest Watch), yet it is not integrated into certification systems because producers fear reputational damage from transparent disclosure. The persistent existence of governance gaps is evidenced by the inadequate enforcement of sustainability criteria. The funding of certification schemes by industry fees creates conflicts of interest that systematically favor lenient interpretation and weak sanctions. To achieve the necessary interconnection, it is important to allocate financial resources to research initiatives in addition to implementing governance reforms that realign incentives. This necessitates a shifting certification funding away from industry fees to public sources, requiring satellite monitoring data as a condition for market access, and establishing independent enforcement bodies empowered to impose market access restrictions in cases of non-compliance. The highest-leverage intervention is LCA standardization with mandatory LUC accounting, which would simultaneously expose greenwashing, enable evidence-based policy, and establish incentives for genuine sustainability improvement. The integration of satellite-based deforestation monitoring into certification systems represents the second-highest leverage point, as it would address the enforcement gap that currently makes certification ineffective. While advanced feedstock R&D is important for long-term transition, it is less impactful in addressing the immediate deforestation crisis driven by 1G feedstocks.

Table 13. Tabulated gaps and suggested research based on urgency

| Gap | Urgency | Suggested research |
|---|---|---|
| Contradictory evidence on palm-oil deforestation [126] | Policy and market decisions rely on uncertain data | Field-level, supply-chain LCA combined with satellite forest monitoring. |
| Integration of socio-economic impacts in LCA | Current LCAs focus on GHG; neglect livelihoods and equity. | Social LCA frameworks that capture income, employment, and gender dimensions [127]. |
| Effectiveness of national biodiesel policies | Regulations exist, yet enforcement and real-world outcomes are unclear. | Quasi-experimental policy evaluation (difference-in-differences) utilizing deforestation satellite data [77] |
| Numbers of apologetic-like approaches for palm oil plantation studies [128] | Investors need comparable sustainability scores. | Development of a Biodiesel Sustainability Index linking finance to LCA, biodiversity, and SDGs [37]. |
| Catalyst innovation for high-FFA waste oils | High free fatty acids hinder conventional trans-esterification. | Laboratory and scale-up studies of hybrid enzymatic-chemical catalysts [129]. |
| Limited study on waste cooking oil effect towards biorefinery performance | This aspect needs to be comprehensively studied, with an aim to formulate effective mitigative action to address te issues related to catalyst deactivation and equipment deterioration. | Long term effect of waste cooking presence to material and or catalysts [103,130] |

To summarize, the gaps mentioned in Table 13 identified in the current literature suggest that, while the enhancement of sustainability in the palm oil industry is of importance, it cannot be the sole focus of future developments. There is an urgent need to investigate complementary feed stocks that do not compete with food security or require additional land. This necessitates a critical examination of Used Cooking Oil (UCO) as a raw material, thereby shifting the narrative from solely managing plantation impacts to actively repurposing downstream waste (see Table 14).

Table 14. Selected upcycling process from [131]

| Source | Upcycling process | Product | Ref |
|---|---|---|---|
| UCO from canteen | Catalytic pyrolysis | Biofuel | [132] |
| UCO frying mustard oil | Fermentation | Bio-lubricants | [133] |
| UCO (rapeseed oil) | Saponification | Biosolid fuels | [134] |
| UCO (canola oil) | Fermentation | Biodiesel | [135] |
| UCO (soybean oil) | Transesterification | Biodiesel | [136] |
| UCO | Co-Digestion with cellulose | Bioplastics | [137] |
| UCO (palm oil) | Saponification | Laundry Soap | [138] |
| UCO | Epoxidation and polyesterification | Polyurethane | [139] |

Kumar et al. (2025) summarized the possible usage of waste cooking oil for sustainable utilization in the future[131]. Their study examined the global potential of Used Cooking Oil (UCO) as a sustainable resource rather than a waste product. It provides a comprehensive overview of the sources and chemical composition of UCO alongside an in-depth exploration of various conversion technologies, including biochemical, thermal, and chemical methods, to transform this waste into valuable products. Their work argues that valorization of UCO is critical for the promotion of a circular economy, offering a dual benefit: it mitigates environmental damage caused by improper disposal (such as water pollution and "fatbergs") while providing renewable feedstock for energy and industrial materials. The following Table 4 presents a list of plausible utilization in the near future, based on the findings of the study.

As depicted in the tabulated information, it can be observed that most upcycling processes involve the production of biodiesel. The nature of UCO, which also contains significant amounts of aldehydes, dienes, alcohols, and heterocycles, presents a challenge for its upcycling.

Another approach to UCO utilization involves the production of sustainable insulating liquids, which has been summarized by Oparanti et al. in 2025[140]. Their study revealed that waste cooking oil (UCO) is a promising, cost-effective and sustainable alternative to traditional mineral oils and fresh vegetable esters as a high-voltage transformer insulating liquid. The findings demonstrate that raw UCO is not suitable as dielectric due to its high acidity and moisture content. However, through the implementation of chemical purification processes, such as transesterification and alkali refining, it is possible to improve its quality to meet the industry standards. These processes result in breakdown voltages up to 48% higher than mineral oil. It may potentially be a “green” coolant and insulator to reduce the “food vs. fuel” dilemma. However, the present study points out a significant problem that UCO is incompatible with Kraft paper insulation over the long term, with the potential for severe degradation from acidic by-products. Therefore, UCO is already well consolidated in the biodiesel sector, but the potential application of UCO in the electrical sector depends on the employment of advanced purification techniques that are required to guarantee operational reliability and material compatibility. Finally, industrial readiness should be also considered for the mitigation of the potential negative impact of the introduction of the UCO to the upcycling processes. Beghetto’s 2025 work explores the future direction of industry[141]. The quantitative findings demonstrate a significant gap between waste generation and recovery. The global consumption of vegetable oil reached over 217 million tons in 2023. This process generated approximately 320 kg of UCO per ton of fuel consumed. However, of the estimated 50 million tons of global UCO production, only 14.1 million tons (28%) are currently recycled. The study also reveals that the European Union only collects about 1 million tons of its estimated 4 to 7.7 million tons of annual UCO output. It is a matter of concern that over 85% of the regions studied lack specific legislation for UCO management, pointing to a critical need for regulatory frameworks to encourage the expansion of non-fuel, sustainable applications. Thus, even within a well legislated area such as the European Union, the implementation of stronger law enforcement for waste cooking oil management remains deficient. This observation is further supported by the findings outlined in the previously mentioned publications. This finding highlights that effective regulation can be the major affecting aspect in mitigating the negative impacts abatements from palm oil plantations.

## 7. Conclusions

This review has demonstrated that the sustainability of palm oil biofuels cannot be reliably gauged through the binary ‘renewable versus fossil’ framings that dominate the current policy discourse. These simplistic mandates have been demonstrated to obscure systemic environmental costs at a range of scales. For instance, feedstock acquisition, which makes up to 95% of total production costs has been shown to cause land-use change (LUC). In 46% of palm oil LCA studies, LUC has been identified as the dominant greenhouse gas contributor. Furthermore, deforestation that threatens over 80% of endangered species in production regions has been identified as a key issue. Institutional frameworks such as RSPO, ISPO and EU RED II have been found to frequently omit LUC data, thereby leading to inflated sustainability credentials through a form of policy enabled greenwashing, further compounded by the absence of standardized LCA protocols with consistent system boundaries and data inventories. This critical methodological gap is problematic in two ways. Firstly, it prevents reliable cross-study comparison and secondly it allows unverified performance claims to persist without rigorous validation while simultaneously impeding precise accounting of logistical trade-offs such as the 607.6 kg $CO_2$-eq per ton emitted during UCO collection and processing. In response to these systemic failures, this review proposes a three-pillar mitigation framework. The first pillar mandates harmonized LCA methodologies with explicit LUC accounting and transparent data inventories. Enforcement of this pillar is through certification schemes and trade agreements, the non-compliance of which will trigger market access restrictions; the second pillar calls for the scaling of used cooking oil (UCO) valorization through regulatory frameworks that incentivize collection infrastructure and biorefinery models diversifying into high-value derivatives. These include oleochemicals, biolubricants, and bioplastics. The generation of internal rates of return sufficient to fund environmental abatement is to be achieved through this process, particularly given that UCO has been reported to achieve 63.7% lower carbon intensity than conventional jet fuel and a 34% reduction in fossil resource depletion. However, only 28% of global UCO is currently recycled and 85% of regions lack UCO-specific legislation. The third pillar directs agricultural expansion onto marginal or degraded lands rather than biodiverse forests, with the objective of achieving substantial emission reductions. This approach has been complemented by the adoption of agroforestry systems integrating oil palms with native species, with the aim of preserving habitat connectivity. Four critical knowledge gaps have been identified as priorities for future research to operationalize this framework: the development of internationally recognized LCA standards for system boundaries, allocation methods, and LUC accounting through ISO or equivalent bodies; regional assessments of UCO availability, collection logistics, and contamination risks to establish realistic supply ceilings and infrastructure requirements; high-resolution spatial datasets capable of distinguishing genuinely degraded lands from ecosystems retaining residual conservation value, thereby preventing 'marginal land' designations from functioning as a loophole for continued deforestation; and the deployment of satellite-based deforestation monitoring systems linked to certification databases to close the persistent gap between policy commitments and on-the-ground compliance. It has been determined that palm oil biofuels have the capacity to contribute to objectives of global decarbonization, provided that production systems are fundamentally restructured to prioritize LCA transparency, circular resource flows, and biodiversity conservation. The absence of such reforms has the potential to result in biofuel mandates risk accelerating the very environmental crises of land degradation, biodiversity collapse, and food insecurity that they are designed to mitigate. The three-pillar framework advanced here is therefore presented as an evidence-based roadmap for aligning economic viability with ecological stewardship, the realization of which requires the collaborative translation of these recommendations into enforceable standards and scalable practices by policymakers, industry stakeholders, and the research community

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### Conflict of Interest declaration

The authors declare that they have no affiliations with or involvement in any organization or entity with any financial interest in the subject matter or materials discussed in this manuscript.

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