Environmental Impacts of Palm Oil Products: What can we learn from LCA?

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Abstract

Quantifying the environmental impact of production systems has become a milestone for agricultural commodity chains. Life Cycle Assessment (LCA) is a unique ISO standardized methodology for estimating the environmental impact of human activities along a commodity chain. In the last decade, LCA has become the worldwide standard for environmental product declarations and the baseline model behind various GHG calculators and certifications (e.g. European Directive 2009; RSPO PalmGHG 2012). Various LCA on palm oil products have shown that the agricultural stage is a major contributor to most of the potential environmental impacts, including global warming, eutrophication and acidification for instance. This large contribution is due to combined important nitrogen (N) input levels in the field and low input levels at the mill and refinery stages. The agricultural stage remains a critical contributor even when the system boundary is extended to palm-based biofuel production. Focusing on global warming impact, main contributors are N-related GHG emissions in the plantation and methane emissions from palm oil mill effluent treatment. The impact from the plantation becomes overwhelming when forests or peatland areas are converted to palm plantations. Meanwhile, impact from palm oil mill effluent can be drastically reduced if the biogas is captured with electricity recovery. While nitrogen inputs are critical, LCA models still mostly rely on global emission factor. A better modeling of the nitrogen balance including a better accounting for soil processes would allow for a more accurate diagnosis of environmental impacts and control levers in plantation management.

Keywords: *Life Cycle Assessment; palm oil; palm biodiesel; environmental impacts; Greenhouse Gases (GHG)*

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1. Introduction

Quantifying the impact of our production systems onto the environment has become a milestone for agricultural commodity chains. Given the various pollution risks (eutrophication, global warming, ecotoxicity), but also mitigation opportunities to reduce global warming for instance, it is crucial to have an understanding and adapted models and tools that allow for identifying best practices in order to reduce environmental impacts from agriculture.

Today there is a single standardized (ISO 14040 series 2000-2006), internationally recognized methodology for estimating the environmental impact of human activities along a commodity chain: Life Cycle Assessment (LCA). In the last decade, LCA has become the worldwide standard for reporting on environmental product declarations (ISO 14025 Type III Environmental Declarations) and the baseline model behind various GHG calculators and GHG certification schemes **[1],[2]** .

LCA is based on two fundamental principles. First, environmental impacts are quantified throughout the commodity chain or “life cycle”, from raw material extraction (“cradle”) to end-of-life of the product or service (“grave”). Then, the impacts are quantified with respect to a functional unit, either a product quantity (one kilo, one car, etc.) or a usage or service (use hours, km, etc.). From a global perspective, the entire life cycle of a product has to be taken into account so that local environmental improvements at one production stage or in one place are not merely the result of problem-shifting to another stage or place**[3]**. Similarly, the comparison based on a common provided functional unit is paramount in order to avoid problem-shifting from one chain to another compensating one. Finally, LCA assesses environmental performance across multiple impacts, such as climate change, acidification, ozone layer destruction, etc. A priori, such a multi-criteria approach does not emphasize any one impact but pinpoints the greatest impacts and their origins at certain production stages. The necessary trade-offs and arbitrations can thus be documented.

In this article, we first briefly present the LCA modeling principle, review the results from published LCA and GHG assessments on palm oil products, and discuss the provided information on palm oil environmental impacts and remaining uncertainties.

2. Life Cycle Assessment Fundamentals

Life Cycle Assessment (LCA) employs a four-stage methodology: 1) definition of the study objectives and boundaries of the system studied from the beginning to end of the chain; 2) inventory of all resource flows used and substances released within the system; 3) characterization or modelling of impacts based on the inventory; and 4) interpretation of the results (ISO 14040 series 2000-2006).

The definition of the study objectives (step 1) implies the definition of the functional unit (FU) and the scope of the system processes to be assessed (e.g. the LCA of FU = 1 t fresh fruit bunch (FFB) includes all processes, from raw material extraction up to the harvest of FFB at the edge of the palm block, in relative proportions to produce 1 t FFB. The flows (resources used and substances emitted) are inventoried (step 2) according to the technical specificities of the studied system. Finally, potential environmental impacts are calculated (step 3) based on a linear model that accounts for dose, fate and exposure of all emissions or resources used that may contribute to various environmental impacts along the commodity chain (Eq.1).

This linear model is a simplification of actual environmental impact mechanisms that does not account for local medium sensitivity or threshold effects. LCA impacts are hence potential impacts and not actual ones. Interpretation of results (step 4) is done in light of uncertainties related to all the previous steps. LCA allows for identifying environmental impact hotspots, process impact contributions and potential trade-offs between impact categories or process stages.

$$\mathrm{I_p} = \sum_i^n m_i \,.\, CF_{i,P} \qquad (1)$$

Where;
$\mathrm{I_p}$ is the indicator for the potential impact *P*

m_i is the mass of the substance *i* contributing to the potential impact *P*

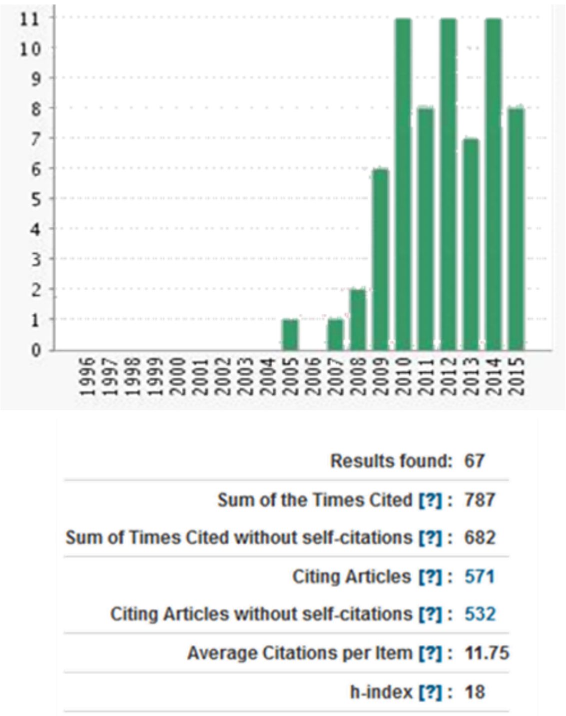
$CF_{i,P}$ is the characterization factor for the contribution of the substance *i* to the potential impact *P*

For example, the impact on climate change is calculated by taking an inventory of all GHG emissions per unit product into account. The emissions are then aggregated into a single impact indicator using IPCC’s linear model, which characterizes what happens to GHGs in the atmosphere and their relative contributions to the global greenhouse effect. Characterization factors in the case of climate change are expressed in CO_2equivalent (CO_2e) based on mass.

Despite the intuitive methodological steps and well-documented guidelines, LCA implementation poses some problems because of insufficient data or scientific knowledge, which gives rise to a number of uncertainties notably when inventorying field emissions and characterizing final impacts. Several characterization methods exist that provide varying environmental profile, i.e. a set of potential impact indicators. In the following section, we review palm oil LCA results from the literature without investigating further the background discrepancies regarding the step by step implementation of LCA.

3. What are the environmental impacts of palm oil products according to publish LCA

Several full or partial LCAs of palm oil products have been published over the last decade (Fig. 1).



Results found:	67
Sum of the Times Cited [?] :	787
Sum of Times Cited without self-citations [?] :	682
Citing Articles [?] :	571
Citing Articles without self-citations [?] :	532
Average Citations per Item [?] :	11.75
h-index [?] :	18

Fig. 1. Published items in each year and citation report from Web of Science (09.2015) searching TOPIC:(LCA+palm oil)

About three fourth of these publications are partial LCA of palm-oil based bioenergy. These publications were notably motivated by the debate on potential net advantages of biofuel compared to their fossil equivalents, and the subsequent release of the European Directive on Renewables (2009/28/EC) that set up sustainability criteria including minimum GHG savings compared to fossil fuels (currently 35%, 50% in 2017 onwards). Therefore, most of the published palm oil-based LCA studies focus on GHG (or climate change impact) and energy balance (or fossil resource depletion)**[4],[5]**. A reduced number of the published LCA actually look over the available panel of environmental impacts provided by LCA methodology. In the following sections, we first review environmental information on palm biofuel, and then we focus on palm oil LCA.

3.1. Environmental impact of palm biodiesel

Most LCA on palm-oil based bioenergy were conducted in Malaysia and Thailand; the few remaining cover predominantly Indonesia (more recent publications), Brazil, Colombia and Cameroon. The great majority of these studies assessed the cradle-to-grave (well-to-wheel) system boundary of palm methyl ester (PME), i.e. including all processes from background input production (e.g. fertilizer manufacture) up to the vehicle tank assuming total combustion or including engine efficiency to calculate final energy and GHG indicators.

Two main energy indicators are commonly used the Net Energy Ratio (NER=output/input) and the Net Energy Gain or Balance (output-input). Although the common LCA indicator for energy use is usually expressed in total used fossil resource equivalents, these indicators give an approximation of the environmental impact in terms of fossil resource depletion. Energy indicators may include co-products or not depending on the allocation ratios or whether system expansion was applied. Results greatly vary among studies (mean NER value around 2.9) notably regarding yields, the handling of co-products the inclusion or not of capital goods (infrastructure), and the discrepancies in terms of transport scenarios (Fig. 2).

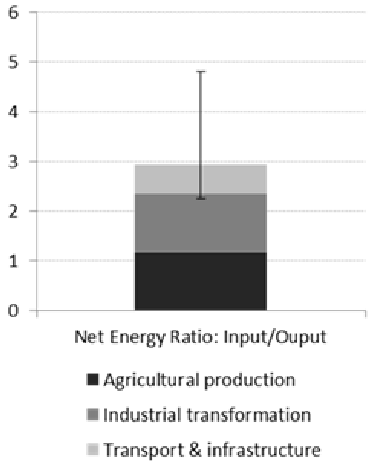


Fig. 2. Comparison of LCA results on palm biodiesel (PME) based on collected data *In* [4]: mean Net Energy Ratio and minimum and maximum values

Despite some differences, all studies highlight the great importance of the agricultural production of palm oil feedstock and the transesterification in terms of energy costs. The production of fertilizers and methanol is the main contributor to the agricultural and industrial phases, respectively. If methanol were replaced by bioethanol, the NER could be improved by 50%**[6]**.

GHG balances also greatly vary among studies. The main influencing factor is the accounting or not for LUC. Moreover, within the studies that include LUC not all use the same methodology to calculate GHG impact, which hinders the comparison. The main varying calculation parameters are the carbon stocks accounted for (considered biomass compartments and amount of carbon released/stored) and the timeframe for amortization[7],[8]. Some of the studies that do not include LUC-related GHG emissions directly in the balance give information on the carbon debt or payback time together with other results. Carbon debt is defined as the number of years needed to recover the carbon loss due to LUC based on the annual GHG savings allowed by the biofuel when displacing the fossil fuel[9],[10]. This carbon debt varies between 8-169 years for palm biodiesel with mean and median values of 54 and 43 years, respectively[7],[9],[11],[12],[13],[14]. The type of previous land use determines the final GHG balance. Net savings of GHG appears possible when palm trees are planted on degraded or grasslands. However, the cultivation of peatland and deforestation are prohibitive in terms of GHG balance (in the upper range of the min-max values).

The mean GHG balance (Fig. 3), accounting for various LUC scenarios, reaches 40 gCO2e/MJ (9 gCO2e/MJ without LUC), but is multiplied tenfold when peatland forest is converted to palm plantations. Compared to fossil fuels, palm biodiesel is disadvantageous in terms of GHG if peatland forests are cleared and if tropical forests are cleared and the palm plantation lasts less than a century[15]. Otherwise, GHG savings between 55-89% compared to fossil diesel can be achieved[7.11-12.16]. Besides LUC, main GHG sources are fertilizers (70-90% in field emissions, 10-30% emissions at manufacture site), methane emissions from palm oil mill effluents treatment when the methane is not captured, and the transesterification process (methanol and electricity)[11],[12],[16],[17].

At least three studies further investigate palm biodiesel environmental impacts[11],[18],[19]. They concomitantly highlighted the important contribution of the agricultural phase to other impact categories, e.g. eutrophication and acidification potentials, carcinogens and respiratory inorganics. Fertilizers greatly contribute to eutrophication and acidification potential impacts. The use of biodiesel in engine also adds to eutrophication and acidification potential impacts[19] and particularly contributes to the impact category respiratory inorganics [18].

3.2. Environmental impact of palm oil

LCA studies on palm fruits and oil are less numerous than those on palm biodiesel but they globally cover more impact categories and provide more details on the agricultural phase[20],[21],[22],[23],[24],[25]. A few studies also focus on GHG assessment[17],[26],[27],[28].

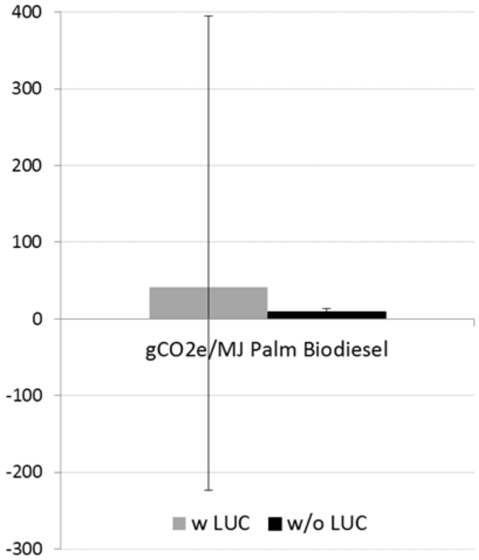


Fig. 3. Comparison of LCA results on palm biodiesel (PME) based on collected data *In* [4]: mean GHG balance per MJ of palm biodiesel (PME) and minimum and maximum values with and without considering land use change (LUC)

As expected, the main contributors to the GHG balance of crude palm oil are the same as for palm biodiesel, transesterification apart, with LUC and peat oxidation being critical, and potentially overwhelming, drivers[21],[22],[29], followed by methane emissions from palm oil mill effluents (POME) treatment and fertilizer-related emissions notably N_2O field emissions[17],[28],[29],[30]. Nevertheless, the impact of POME can be significantly reduced if biogas is captured at the mill[17],[28],[31],[32] or, to a lesser extent, if raw or partially treated POME are injected in the composting process[33],[34].

In a pilot application of Palm GHG (RSPO GHG calculator, Chase et al. 2012) on mills in Southeast Asia and Latin America, the average GHG balance was 1.67 tCO2e/t CPO (Crude Palm Oil) and ranged from -0.02 to +8.32t CO2e/t CPO [28]. Across the mills without supply from peat area, land clearing, POME methane emissions, and fertilizer-related emissions represented 41-80%, 15-35%, and 3-19% of total GHG emissions, respectively. The impact of fossil fuel use was not significant (0-5% and 0-2% of total emissions at the field and mill levels, respectively). This low impact was due to a low mechanization level in the plantations and the recycling of numerous residues that provides heat and power to operate the mill (with potential excess electricity production). Most of field fuel use is dedicated to FFB transport. Hence, the impact of fuel use may greatly vary according to FFB collection logistics.

Published GHG balances (or climate change impact indicator) range between -0.55 and 24 tCO2e/t CPO with median values around 1-2 tCO2e/t CPO when LUC concerns mixed previous land uses and less than 10% peatland, and methane is not captured[17],[21],[24],[35].

Looking at the other impact categories, the agricultural phase remains the main contributor to most of the impact except for human toxicity or respiratory inorganics impact to which boiler emissions contribute mainly[25],[35]. Mill emissions can also contribute to eutrophication which is driven by nitrogen- and phosphorus-compound emissions. The main eutrophication factors at the agricultural stage are nitrate leaching and phosphorus and nitrate run-off. Other N-compound emissions also contribute to acidification and photochemical ozone impact categories. While palm oil generally performs worse than other oil crops on climate change impact due in particular to LUC, it performs better than rapeseed oil regarding eutrophication, acidification, ozone depletion and photochemical ozone impacts[24].

4. What do we still need to learn about palm oil LCA?

There exist 13-18 impact category indicators in standard LCA methods currently used (RECIPE, ILCD). Many LCA impact indicators remain to be more widely explored across palm oil production systems such as for instance the impacts of pesticides such as paraquat or glyphosate on terrestrial or freshwater ecotoxicity, or the impact of irrigation systems on water depletion. Given the high contribution of fertilizers to environmental impact of the agricultural phase, the eutrophication and acidification impacts related to nitrogen and phosphate inputs would also need to be further investigated.

Independently from the system boundaries studied, the agricultural phase, and in particular fertilizer inputs, plays a key role in determining the final environmental profile. It is hence paramount to adjust fertilizer inputs to foster productivity while limiting loss to the environment. To do so, there is a critical need for adapted models (mechanistic or operational models) that would allow for more precise estimate of field emissions linked to fertilizers. Indeed, the great majority of LCAs used IPCC emission factors to estimate nitrate leaching and run-off as well as ammoniac or nitrous oxides emissions. These emission factors are poorly calibrated for tropical regions[36],[37],[38] and do not much take into account the specificities of perennial cropping cycles such as palm plantations. In a recent review, we emphasized on the fact that the structure and long-term evolution of oil palm plantation induce specific spatio-temporal patterns in nitrogen fluxes that are poorly quantified and need further research. This review also highlighted that nitrogen losses through leaching and volatilization may be important and all nitrogen gaseous losses remain very uncertain[39]. More field measurements are needed to establish more relevant emission factors. New knowledge and model developments are also expected to account properly for the comprehensive role of organic fertilizers in soil quality and potential field emissions.

Research projects are on-going that will shed some light on involved processes in order to reduce uncertainty in LCA results. Development work on other approaches, such as agro-ecological indicators, can be complementary as they may allow for a better accounting of local conditions and practices to build-up the LCA inventories.

There are other challenges relating to impact modelling in LCA. On-going researches on LCA impact characterization also include the development of new impact characterization such as the land use impact category[40],[41] that has been upgraded in the new Ecoinvent version (v.3), biodiversity impact linked to land use including soil biodiversity, etc.

Finally, the limits of the linear model may be overcome by developing regional characterization factors that can be used to adapt the linear model to the sensitivity of the local host environment. Such factors are particularly critical in the case of localized impacts that are more sensitive to changes in the immediate environment, such as eutrophication, or resources unequally distributed on the global scale, such as water in dryland areas. Such regional factors have not been yet much developed in regions where palm plantations are established and in the context of LUC that may particularly affect the medium sensitivity during transition phase.

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