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DOI:
10.1016/j.rser.2018.05.066

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Document Version
Publisher's PDF, also known as Version of record

Citation for published version (Harvard):
Archer, SA, Murphy, RJ & Steinberger-Wilckens, R 2018, 'Methodological analysis of palm oil biodiesel life cycle studies', *Renewable and Sustainable Energy Reviews*, vol. 94, pp. 694-704.
https://doi.org/10.1016/j.rser.2018.05.066

Link to publication on Research at Birmingham portal

Publisher Rights Statement:
Checked for eligibility 19/07/2018

First published in Renewable and Sustainable Energy Reviews
https://doi.org/10.1016/j.rser.2018.05.066

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Renewable and Sustainable Energy Reviews 94 (2018) 694–704

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Methodological analysis of palm oil biodiesel life cycle studies

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ARTICLE INFO

Keywords:
Life cycle inventory
Palm oil fruit
Crude palm oil
Biodiesel

ABSTRACT

Biodiesel is a renewable vehicle fuel based on biomass. Although environmental benefits can be assumed, both positive and negative impacts have been stated in the past, raising some doubts on the effective environmental performance of biofuels. They therefore need to be carefully examined through the established methods of Life Cycle Analysis (LCA). Such studies, though, have been known to give conflicting results and, for non-specialist users of environmental performance information, such variations in literature between studies will be a cause of concern.

Following the principles of the ISO 14040 and 14044 standards for LCA, we have explored the variations in LCA methodology and parameter choices in a comparative analysis of 11 published studies of the production of biodiesel from palm oil. This study highlights inconsistencies between individual studies in aspects such as data coverage and completeness, system boundaries, and input and output streams. The importance of including factors such as plantation carbon sequestration and land use change demonstrates a need for consistent and appropriate methodologies. These factors are some of the most important drivers for variation in the results of LCA studies of palm oil systems, as well as being necessary for a comprehensive perspective. The results of this study also highlight the importance of geographical location and the fact that studies are often based on very limited data sources.

A variance analysis identified the greatest source of variation across the chosen data sets, highlighting key methodology steps and pointed at pitfalls in employing supposedly environmentally benign technologies. The paper offers suggestions to i) assist inter-study comparisons, ii) offer non-LCA specialist users insight into the causes of variable results between LCA studies, and iii) guide further in-depth research.

1. Introduction

As the human population increases, the growing demand for food, energy, water, and materials has the potential to considerably increase the amount of pollutants and greenhouse gases (GHG) being emitted into the environment [1]. In the UK, the total GHG emissions in 2014 were 514.4 Mt CO_{2eq}, of which UK electricity generation emissions accounted for 159.5 Mt CO_{2eq} (31%) and transport for 118.3 Mt CO_{2eq} (23%) [2]. Policy makers and supporting bodies are looking to increase the sustainability of all sectors and, with regard to reducing the total GHG emissions, energy and transport are the two highest impacting sectors. Reductions within the energy sector will accrue as renewable technology deployment increases. In the transport sector it is expected that improvements will predominately be in the fuels used and in improving drive train performance, aside from the increasing tendency of European governments to phase out vehicles with internal combustion engines in favour of electric mobility and alternative fuels.

Biodiesel is an alternative transport fuel to fossil diesel. It is renewable and can be derived from several feedstocks, such as vegetable oils (like rapeseed and jatropha [3–5]) and recycled waste cooking oil [6], amongst others. The production of biodiesel predominately utilises transesterification to produce a monoglyceride biodiesel (and ~10% glycerol co-product of total biodiesel yield) from plant oil precursors, with more recent movements adding a catalytic hydroprocessing stage [7]. The principal advantages claimed for biodiesel are that it is renewable and, although the 'Tank to Wheel' energy density of biodiesel at 39 MJ/kg is marginally lower than the 42.8 MJ/kg of fossil diesel, its GHG emissions are lower [8–10]: 3 kg CO_2/litre biodiesel versus 3.16 kg CO_2/litre fossil diesel. Including factors such as feedstock carbon sequestration during growth [11] and land use change [12–16], two influential factors for biofuel production, is becoming increasingly important, as they directly contribute to the overall carbon impact of the biodiesel.

Abbreviations: LCA, Life Cycle Analysis; GHG, Greenhouse Gases; LCI, Life Cycle Inventory; POBD, Palm Oil Biodiesel; FU, Functional Unit; CPO, Crude Palm Oil; FFB, Fresh Fruit Bunches; EFB, Empty Fruit Bunches; POME, Palm Oil Mill Effluent

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https://doi.org/10.1016/j.rser.2018.05.066
Received 29 August 2017; Received in revised form 14 May 2018; Accepted 28 May 2018

It is important to recognise, therefore, that considerable scope remains for transparent and unbiased methodologies in Life Cycle Analysis (LCA) studies consistent with the desire for objectivity. It follows that full uniformity between different LCA studies is necessary, although today not yet achieved. Thus, in this paper's analysis, we have sought to comment upon the methodological aspects of Palm Oil Biodiesel (POBD) LCA studies that we deem to fall outside of a helpful application of LCA's inherent flexibility. The findings are hoped to help non-LCA-specialist users of LCA studies to assess results by checking for stringency of the analysis and any data sets published. This will be especially important when the LCA results will be used within further analysis and comparisons leading up to political strategy decisions.

There are various review studies that address analysis comparability. Bessou *et al.* [17] reviewed 70 biodiesel LCA studies, grouping similar work in regard to feedstocks, such as palm oil, jatropha, sugarcane *etc*., and highlighted LCA parameter information such as geographic location, functional unit (e.g. 1 kg or 1 MJ or 1 t Palm Oil Mill Effluent (POME) *etc*.), system boundary (cradle to grave/gate/tank *etc*.), and which impact assessment criteria was used (IPCC 2006/CML-IA/Energy Balance *etc*.) [17]. Malça *et al.* [4] conducted a similar study with 28 comparative biodiesel LCA's, including their own study. It covered information such as the type of LCA method (attributional), whether Indirect/Direct Land Use Change was included or not, Energy requirement, GHG intensity, as well as geographic location, to name but a few. A meta-analysis was also published in 2012 by Manik and Halog [18], who reviewed a number of palm oil LCA studies, focussing specifically on impact assessments and energy balances. Another comparative study is rom available Rocha *et al.* [19], who compared 12 Brazilian biodiesel LCA studies, ten of which were from soybean (five) and palm oil (five) feedstocks.

This paper presents the inventory dataset summaries side by side, comparing studies regarding completeness, since some papers did not display data for all the parameters listed. In regard to these comparison studies for biodiesel LCAs, few papers include details on whether the study complied with the ISO LCA standards, and no papers were explicitly clear about whether consequential or attributional LCA approaches were utilised.

There is also a variation in the way that reports are presented from large organisations like the Royal Society, UNEP GEF, IFEU, WWF etc. and research/production boards like the Roundtable on Sustainable Palm Oil, as some will only look at carbon or energy, and rarely with quantity. On the other hand, there are increasing efforts across multiple research fields in aligning divergent studies and normalising them, so that the results can be presented in a comparable and calibrated manner [20]. This was addressed by Farrell *et al.* [21] through normalising LCA data to gain an overall understanding, as well as by Manik and Halog [18].

The above considerations formed the basis for the exploration of possible ways to assist non-, or less-specialist users of LCA to interpret the environmental profile outcomes of different LCA studies. By providing a perspective on the structuring of LCA frameworks, we intend this paper to provide some significance to this research field, focusing on comparative assessments of environmental assessments (Section 3).

Biodiesel production from palm oil was selected for this examination because it is a mature process and, as a highly productive and well-established crop system, palm oil offers much future scope for further generations of biofuels, bioenergy and bioproducts. Calibration of results and assurance that the environmental profiles of such palm oil products meet sustainability requirements will be a key component of any policy and investment decisions concerning the future development of palm oil and other biomass-based systems. From an initial collection and overview of biodiesel based papers, as input to the analysis presented here, over 100 studies were relevant to palm oil, from these, 17 studies with adequate inventory data were selected, out of which only 11 had sufficient breadth of coverage of the palm oil supply chain, relevance to POBD, and had been published in refereed, archival journals. Having located a number of review articles on palm oil with only four to eight studies, we felt 11 studies were sufficient for our purpose. These were analysed to evaluate the reasons for variation regarding the results of their Life Cycle Inventory's (LCI), and consequently their Impact Assessments.

Having selected POBD as an exemplary topic, the objectives of the in-depth study were:

i) To develop a generically-representative LCI dataset of a 'Well to Tank' POBD system (from palm oil biomass production to biodiesel production, ready for use) based on available published inventory data within literature.
ii) To explore and assess the data extracted from the studies and discuss the variations found across published data in the literature.
iii) To explore the variance of LCI outcomes, focusing on discrepancies in specific parameters.
iv) To examine how methodological and other choices could affect the outcomes of POBD studies.

2. Materials and methods

In order to fulfil mentioned objectives we reviewed LCA studies on POBD, and built a generic LCI to reveal sources of discrepancy in published findings and to identify ways of minimising such variation in LCA study outcomes.

2.1. *Selection of studies*

There are multiple strategies that can be utilised in order to produce a robust LCI data set from published data. The most common methods used are systematic review and meta-analysis. In this study, a systematic review was conducted to identify appropriate sources from literature published between 2007 and 2014, using online resources such as Science Direct [22] and official journal websites, including but not limited to Elsevier [23,24] and Springer [25], to enable development of a normalised, generic LCI for POBD based on a meta-analysis approach. Further literature collection was attempted between the periods of 2015 and 2018, with only three sources [26–28] being found to meet similar criteria as the studies assessed in this paper; the latter of which cited most of them. However, all three papers were missing key data outputs, and/or contained data very similar to those already investigated, and so would not add anything new at this time. There were also no compatible papers found for 2017 or 2018; only one assessing the composition of palm fruit bunches [29], which has been utilised later in this paper.

Therefore, the existing publications identified between 2007 and 2014 were deemed sufficient for the current review. As a consequence of this, we did not make use of databases and LCA software for this study and relied soley on the reported data, just as any potential user of this literature would have to do. As a result, a production system analysis was adopted, from an established plantation through to biodiesel production, but not biodiesel use.

2.1.1. *Decision tree*

During background research, it was found that many whose titles suggested relevance to LCA of biodiesel were either unrelated to palm oil [30–34], had incomplete data sets [35,36], or were incompatible with other studies - typically due to data that could not be normalised or varied substantially in terms of parameters, system boundaries, and/or data coverage. These variations limited their value for assimilation into a generic dataset, especially due to rather few studies having consistent data fields. The following decision tree was used to determine the suitability of a published article for use in this paper (Fig. 1).

At the highest level in Fig. 1, papers and other publications were

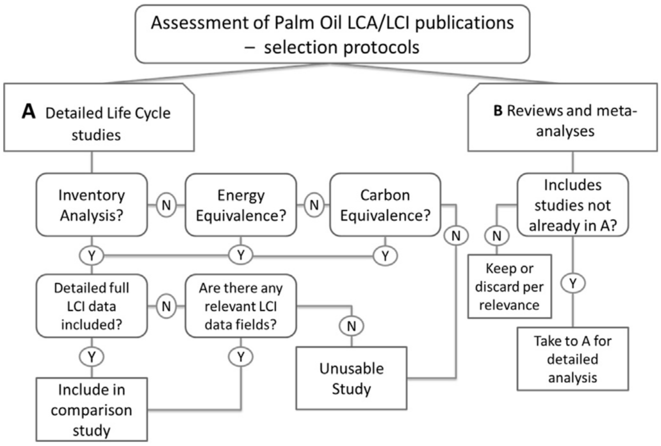

Fig. 1. Palm Oil LCA/LCI publications for comparison analysis - identification and selection decision tree.

reviewed for their methodological basis and the comparability of inventory data within the overall goals of this study. Articles passing this high-level filter were then considered under either 'Route A' or 'Route B'. 'Route A' represents research papers with 'complete' published inventory data sets and, depending on the information content, relies on how compatible they were with other relevant studies for LCI and overall LCA evaluation. 'Route B' addresses review articles and meta-analyses of the subject area. These were useful for data and normalised outcomes and as sources of additional studies for individual analysis under 'Route A'.

Summary Table 1 identifies the countries of origin of the investigated studies and whether LCA environmental impacts/an energy balance were included in the results. In the initial meta-analysis, 150 studies were identified to cover relevant research topics but, within these, only 17 studies [35,37–52] had a suitable level of transparent data sets. Table 1 also lists the three types of LCI data and Impact Assessment categories covered within each study. The categories, based on the ones listed in LCA database software such as 'SimaPro' and 'Gabi', which some studies used, use a variety of impact assessment methodologies, including 'CML-IA baseline', 'ILCD 2011 Midpoint+ ', and 'IMPACT 2002 + '. Alternative impact assessment methodologies differ through which impact categories, and/or resource/emission contributors are used. In order to cover all impact methodologies, the categories were aggregated under the four main areas: Human Health, Ecosystem Quality, Resources and Land Use Change. Within these categories, the most frequently found data consisted of Global Warming Potential (GWP-100a/Climate Change/GHG), Eutrophication Potential, Acidification Potential, Fossil Fuel Resource Use, and Land Use Change; all except the latter are typical of the 'CML-IA baseline' methodology.

In many cases, published papers and reports only cover one critical environmental impact (usually GHG emissions or GWP-100a). Only half of the studies in Table 1 assessed the potential impact of land use change; four of which were further assessed in stage two of this paper. Of the papers that did assess land conversion, the majority assumed rainforest – both primary and replanted, cultivated grasslands, and/or peatland [35,40,45,47,48]. In addition, only 2 studies performed every impact category (Nazir *et al.* [41] and Yusoff *et al.* [47]), and a quarter of studies investigated more than two impact categories. Therefore, due to data inconsistencies across the majority of impact categories, Impact Assessment was excluded from this paper, as it would be neither beneficial nor impactful to the field. We therefore focused on the meta-analysis and LCI aspects of our study to produce a generic LCI, with coefficients of variation, from this literature. This in turn would allow us to analyse the studies and identify their methodological variation outcomes for non-LCA-specialist users. The limitations of this approach are considered in the discussion of this paper.

The '*Comparable'* column in Table 1 represents an overview of the suitability of the articles' base data and Functional Units (FUs) from a variation of complete to somewhat sparse studies. 'Acceptable' studies contained data that was comparable either directly or through very limited re-calculation or conversion, 'Reasonable' studies covered at least two of the three core LCI data categories but required conversion/data reworking of the energy equivalence data, and 'Limited' studies had data which could not be directly compared despite covering the necessary LCI data categories. This process led to a reduction in the

Table 1
LCI and LCIA content of the papers selected for in-depth analysis in this study.

Reference	Study Lead Author	Geographic Location	Comparable	LCI			Human Health						Ecosystem Quality			Resources		Land Use Change
				Quantity	Energy	Carbon/Emissions	Carcinogens	Respiratory Organics	Respiratory Inorganics	Climate Change/GWP/GHG	Radiation	Ozone Layer	Ecotoxicology	Eutrophication	Acidification	Metals/Minerals	Fossil Fuels	Decreased Diversity
[x]	Costa, 2007	Brazil	R	R														
[x]	Queiroz, 2012	Brazil	L	R	R													
[x]	Souza, 2010	Brazil	A	R	R	R				R								
[x]	Achten, 2010	Cameroon	R	R						R				R	R		R	R
[x]	Harsono, 2012	Indonesia	A	R	R	R				R								R
[x]	Nazir, 2010	Indonesia	R	R			R	R	R	R	R	R	R	R	R	R	R	R
[x]	Kamahara, 2010	Indonesia	R	R	R													
[x]	Yusoff, 2007	Malaysia	R	R		R	R	R	R	R	R	R	R	R	R	R	R	R
[x]	Choo, 2011	Malaysia	R	R		R				R								
[x]	Pehnelt, 2012	Malaysia	A	R	R	R				R								
[x]	Wicke, 2008	Malaysia	R	R		R				R							R	R
[x]	Yee, 2009	Malaysia	L		R	L				R							R	
[x]	Uusitalo, 2014	Mixed	A	R	L	R				R								R
[x]	Papong, 2010	Thailand	R	R	R													
[x]	Pleanjai, 2007	Thailand	R	R	L	L												
[x]	Patthanaissaranukool, 2013	Thailand	R	R	R	R				R						R	R	R
[x]	Pleanjai, 2009	Thailand	R	R	R													

A = Acceptable; R = Reasonable; L = Limited; and Blank = No data article set down from 17 studies to 11.

Throughout the assessment of numerous articles, it was clear that different publications have different methodological structure within this area of LCA research. As a result, a detailed LCI on POBD was produced, with the aim of delivering a comprehensive model dataset. The results gained seek to give insight on the divergence in evaluation and to develop further understanding of how this variance in results may be mitigated within the LCA approach and methodology.

2.2. Development of generically-representative LCI dataset for POBD

The model POBD LCI was developed following the principles of ISO 14040 and 14044 standards [53,54].

2.2.1. Goal and scope

The aim of the study was to conduct an overview of POBD production, assessing the inputs and outputs throughout the palm plantation, Crude Palm Oil (CPO) processing plant and biodiesel production plant stages. As the use phase was not included, excluding fuel distribution and the combustion phase, the resulting assessment is typical of a ‘Well to Gate’ analysis.

2.2.2. Functional units

The Functional Unit (FU) of this study is ‘the production of 1000 kg POBD’. The demands for CPO and Fresh Fruit Bunches (FFB) have been ratioed accordingly to correspond to a reference flow of 1000 kg POBD. There are three expressions for this study with the following data types:

- Quantity data: kg/1000 kg POBD
  This is used within the inventory for input substances, such as fertilisers and herbicides. Quantity values are based on the amount of FFB output, which in turn is determined by the amount of CPO required to convert into the POBD FU. This is due to CPO and FFB being the key ingredients for POBD.
- Energy equivalence data: MJ $_{eq.}$/1000 kg POBD
  The quantity of several input substances (e.g. fertilisers, herbicides) is determined by the amount of FFB output, which in turn is determined by the overall 1000 kg POBD FU. The energy equivalence value for such substances is directly related to the FU, in regards to its energy content, and in the cases of fertilisers and herbicides, the amount of energy required to produce them.
- Carbon equivalence data: kg $CO_{2\,eq.}$/1000 kg POBD
  The carbon equivalence of the inputs and outputs is also included in this assessment, but not the combustion of the POBD due to it being outside of our system boundary. Like energy, all the carbon equivalence values are calculated on an FU basis.

2.2.3. Dataset collection, normalisation and completion

The individual elements of inventory data were extracted from the 11 studies passing the systematic review and organised under three key stages of POBD production: FFB plantation (Stage 1), CPO processing (Stage 2), and POBD production (Stage 3). Each study presented slight to substantial differences in the quantities of FFB, CPO, and POBD, so all the key inventory data were homogenised so that all studies utilised the same FU. As shown in Table 1, some studies had only one set or mixed sets of inventory data consisting of quantity, energy and/or carbon equivalence data types.

Studies with only energy and/or carbon equivalence data were used to assist in completing missing fields from other studies, taking care to only use data from similar geographic locations to fill in gaps. Palm Oil can only be produced in certain climatic zones, namely between the latitudes 10–20° North and South of the equator [48], so the inaccuracy factor from using data from similar geographies is minimised. As few studies have previously contained all three data types across the chosen fields, this approach was adopted in order to produce a model process chain as comprehensive as possible. The development of the meta-analysis resulted in a normalised LCI dataset that progressed from some of the individually very sparse, incomplete data in any given publication. The data fields chosen were based on frequency of occurrence across the 17 studies. Of these fields, many studies only contained less than 25% when the three data types were originally extracted from the source publications. These data sets were then normalised and geographically completed up to a level of 95% of the fields. This was achieved by going back to fundamentals, such as carbon equivalence or $MJ_{eq.}/kg$ values, and completing missing data by using data from geographically comparable studies. For instance, overall energy equivalence and carbon equivalence were calculated using Eqs. (1) and (2), respectively.

$$EnergyEquivalence\,(MJ_{eq.}/kg)*quantity\,(kg) \tag{1}$$

$$CarbonEquivalence\,(kgCO_{2eq.}/kg)*quantity\,(kg) \tag{2}$$

This resulted in converting what was once 17 sets of incomparable POBD LCI's to 11 comprehensive data sets, which covered quantity, energy, and carbon equivalence in a comparable, consistent format.

3. Results

The normalised values of the resultant LCI dataset of the POBD production process are presented below, together with detailed presentation of the ranges of results and uncertainties deriving from the individual sources.

3.1. LCI structure – process overview

In order to produce 1000 kg POBD, 5123.6 kg ± 36% of cultivated FFB from the Palm Oil Plantation are fed into the CPO processing stage. Within the CPO plant, the FFB are sterilised in an autoclave for ~90 min at ~125 °C, ~1.37 bar [49,51]. The fresh fruit is then stripped from the fruit bunches and mashed under steam-heated conditions in a process called ‘digestion’. The CPO is extracted, typically yielding an amount of 987.9 kg ± 15% as the mashed pulp is pressed, before being centrifuged, purified and stored at 60ºC [49,51]. Additionally, the fibre and nuts are removed from the press. The nuts are then cracked, separating the kernels from the shells so they can be sold. The fibre and shells can be used as boiler fuel to produce carbon natural electricity and steam on site [49,51,55], due to carbon sequestration during biomass growth. This resulted in allocation of avoided grid electricity during the crude palm oil production stage. An improvement of this could be converting the POME, which is the waste water from the ‘digestion’ process, and the Empty Fruit Bunches (EFB) into biogas in an Anaerobic Digester. This biogas could then be used in a boiler, turbine, or fuel cell to produce electricity and heat (for steam production); which some studies did consider [37,39,40,42,43,52].

The CPO is then passed on to the next stage, Biodiesel Production, where conventionally it is transesterified using methanol and sodium hydroxide, to finally yield 1000 kg of POBD and 110 kg of glycerol, which are produced together [56]. During this process triglyceride oils are converted to methyl esters through the addition of methanol. This reduces the molecular weight to one-third, reduces the viscosity by a factor of eight, and increases the volatility. The methyl esters are then washed, so the glycerol is finally gravitationally separated overnight [55], resulting in a more refined biodiesel product.

The Sankey diagram in Fig. 2 provides a graphical representation of this system. It also demonstrates the additional inputs, wastes, and primary/secondary product flows (fresh palm fruits/crude palm oil) to the final stage product, POBD, with its glycerol by-product. The majority of studies utilised wastes and by-products either for onsite energy, or sold them for additional revenue. Some of the studies considered methanol recovery and reuse, and most did not discuss the amount of washing wastewater produced. Therefore, it could be assumed that the water and methanol inputs would equal the washing waste outputs, but

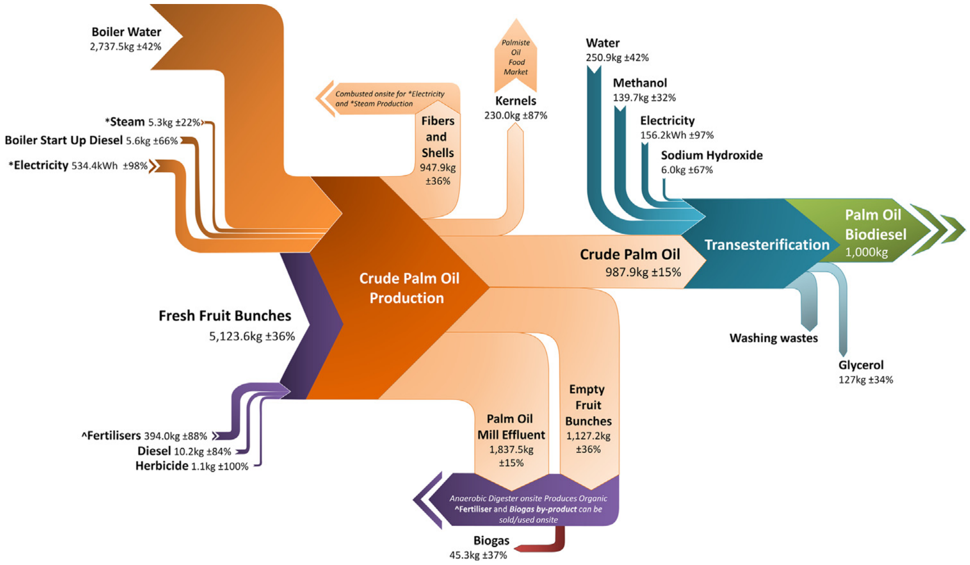

Fig. 2. LCI quantity flows based on 11 LCA study references [37,39,40,42,43,45,47,49–52,57].

with varying degrees of evaporation and potential losses from the system, it was not possible to calculate these amounts.

Fig. 2 highlights the flow of materials and resources. Inspecting the graph offers some insight into not only the current coefficients of variation between the key studies in this paper, but also opportunities for improving the process efficiency. For instance, it can be seen that the amount of water used in the CPO processing stage boiler, for producing steam, is one of the highest inputs within the system, of which most exits the system within the POME. This indicates possibilities of heat recovery and possibly water management.

The CPO processing stage generates several biomass co-products coming from the separation of the FFB. The EFB and POME can be treated in ponds onsite and then used as a substitute for inorganic fertiliser, and the biogas produced from POME could be converted to electricity. Most studies currently use a mix of grid electricity and onsite generation from waste biomass. The fibres and shells are combusted to produce electricity and steam for the CPO processing stage, and the kernels are typically sold on for palm kernel oil production.

3.2. LCI – range and variation

3.2.1. Analysis of variations within inventory analysis data

3.2.1.1. Quantity data. The quantity data was analysed first, as the energy and carbon equivalence data had to be synthesised based on this data set. The FU was defined as 1000 kg POBD for all 11 studies and the amount of FFB and CPO were amended accordingly (Figs. 3, 6 and 7).

The range of data generated varied considerably for certain studies, as demonstrated by the Pleanjai *et al.* [51] study. Table 2 provides a summary of the LCI data generated. For the production assessments in Figs. 4 and 5, the data in Table 2 was used to calculate a CPO average (1055 kg/1000 kg POBD) and an FFB average (5180 kg/1000 kg POBD). These values were not used anywhere else except in the variance analysis to demonstrate differences above and below the median data values.

Figs. 3, 6 and 7 are graphitisation's of the data from Table 2, using a spider diagram to demonstrate the variation of data across the 11 chosen studies. In terms of the parameters (Plantation, Processing, and Transesterification), they all include each stage's respective inputs and outputs, including products passed onto the next stage. It can be seen that the data sets are not entirely consistent and there are fluctuations across the chart due to missing data.

In Fig. 3, within the 'Plantation' stage, the FFB makes up a majority of the quantity for most studies, Pleanjai *et al.* [51] forming an extreme. This is because of the amount of fertiliser that Pleanjai *et al.* [51] assume to be required, in which the other studies differ in analysis. They also claim to high quantities in the 'Processing' parameter, which can also be seen in their follow-up review [52], but this is predominantly because they have more complete data sets than the other studies. These have some values missing, for instance Achten *et al.* [40], who provided little processing data.

The reason the key indicators of the POBD system (FFB/CPO/POBD) have received so much attention is because of the extent of the missing or unknown data for energy and carbon equivalence values. The other parameters have been added to demonstrate how much incomplete data sets can obscure the results, although most fields have been filled with similarly sourced data. The common known values for the FFB and CPO parameters are that for every 1000 kg CPO produced approx. 5000 kg FFB are required [36]. Figs. 4 and 5 highlight the extent of study variations based on these findings.

The horizontal dotted lines in Figs. 4 and 5 show the averages of the FFB and CPO production data sets, respectively. The solid lines demonstrate which studies are either close to or far from average. Both Pleanjai *et al.* [51,52] studies are consistently above average, due to having more complete data sets. Conversely, Papong *et al.* [50] is under average for both. Reasons for these variations also consist of geographic locations, plantation sizes, technology efficiency and age, and production methods.

Souza *et al.* [39] and Kamahara *et al.* [42] are the two most consistent studies for both FFB and CPO processing, in accordance with average production. The low CPO value of Patthanaissaranukool *et al.* [49] in Fig. 5 is also one of the studies to have more consistent FFB production, whereas Choo *et al.* [43] has less consistent FFB data than CPO with the averages. If methodological deviations are cancelled out, possible parameter variations could be influenced by ageing technology, plantation harvest technique variations, or lower quality of harvests due to climate impacts.

3.2.1.2. Energy equivalence data. The energy equivalence data (Fig. 6) was produced using reported energy equivalence values for inventory data (Table 2). The FU was set at the energy equivalence of 1000 kg POBD for all 11 studies and equalled 39,600 $\mathrm{MJ}_{eq.}$/1000 kg POBD. The CPO values were slightly more consistent for energy equivalence data compared to quantity data, fluctuating closely around 38,121 $\mathrm{MJ}_{\mathrm{eq.}}$/1000 kg POBD ± 10%. The FFB dataset had higher variation between studies, at 78,040 $\mathrm{MJ}_{\mathrm{eq.}}$/1000 kg POBD ± 33%.

Both Pleanjai *et al.* [51,52] studies have the highest energy values

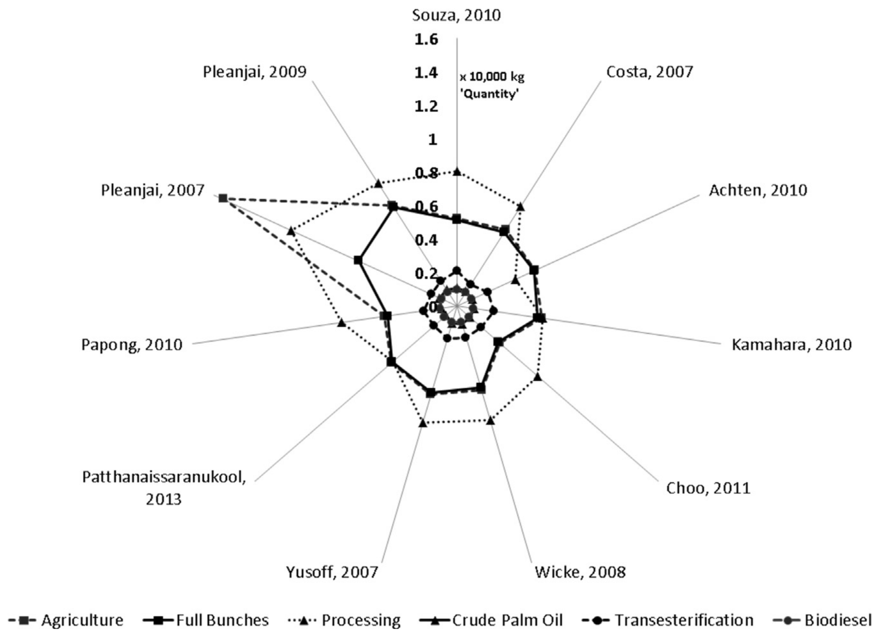

Fig. 3. Input and output quantity data variations for 1000 kg POBD FU for 11 LCA study references [37,39,40,42,43,45,47,49–52,57].

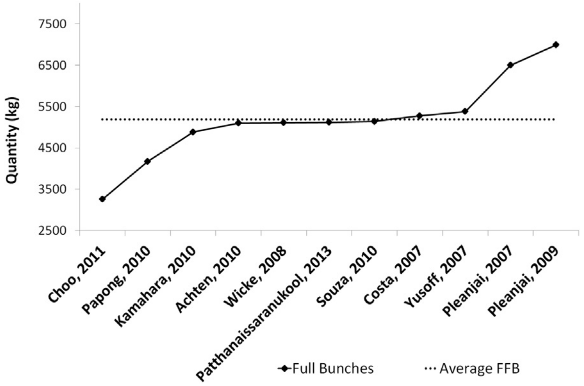

Fig. 4. Quantity of FFB necessary for producing 1000 kg POBD vs the average from 11 LCA study references [37,39,40,42,43,45,47,49–52,57].

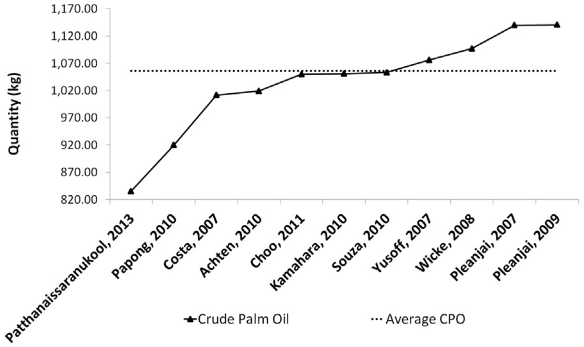

Fig. 5. Quantity of CPO necessary for producing 1000 kg POBD vs the average from 11 LCA study references [37,39,40,42,43,45,47,49–52,57].

again, but as before, this is because of their more complete data sets and higher energy data for the key indicators (FFB/CPO/POBD). The data from the other studies is reasonably consistent, demonstrated by the homogenous patterns, Achten *et al.* [40] being the exception due to their lack of processing data.

It should be recognised that the angularity of Fig. 3 is significantly higher than in Fig. 6, demonstrating that energy data is in better agreement across the studies than quantity data. However, as the energy equivalence data is directly derived from the quantity data, it is curious how Fig. 6 is more homogenous than Fig. 3, as it would be expected that similar data patterns would be produced. This illustrates the importance of evaluating more than one aspect in order to get a more complete assessment of inter-study heterogeneity.

3.2.1.3. Carbon equivalence data. The carbon equivalence data (Fig. 7) was the most incomplete data set, having most fields missing due to lack of published data and/or unknown values. Like the data for energy equivalence, this data was produced by using carbon equivalence or 'kg $CO_{2\,eq.}$' values from other literature for the relevant items (also shown in Table 2). POBD data was set at the same carbon equivalence value across all 11 studies: 2823 kg $CO_{2\,eq.}$/1000 kg POBD. This was calculated using the amount of combustible organic carbon content within the biodiesel methyl ester that could produce carbon dioxide when used in an internal combustion engine.

The carbon equivalence for CPO was calculated to be around 3006 kg $CO_{2\,eq.}$/1000 kg POBD ± 15%, which was based on a POBD organic carbon content of 83%. The FFB carbon values were calculated the same as CPO, based on 31% organic carbon content and quantity. There were some significant variations for 'Processing', due to the lack of data set completeness, as before, much unlike the more downstream data sets that show greater consistency between studies. As Achten *et al.* [40] is the only study for Cameroon, and no comparable geographical site data available to fill in the gaps, its incompleteness demonstrates how the reliability of such sources can be easily corrupted.

3.2.2. Meta-analysis results

The meta-analysis results show that the level of comprehensiveness affects the comparability of studies in terms of transparency, accuracy and reliability. Although all the data sets provide reasonably consistent stage three POBD data, the input data for stage one FFB and stage two CPO data are more heterogeneous, due probably to specific difficulties with individual items in gathering data and/or variations of the life cycle methodologies applied. For instance, the amount of CPO produced depends on the different contributions of mass for the FFBs as they go through the 'Processing' stage. This is demonstrated in Fig. 8; each bar represents what is present inside each total output of FFB/FU.

There are eight complementary and complete data sets

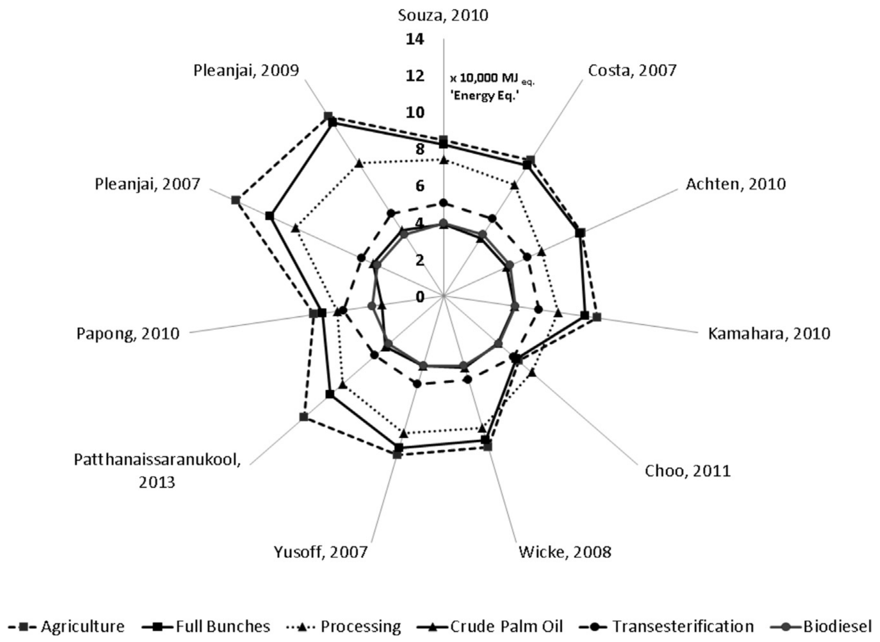

Fig. 6. Energy equivalence data variations for 1000 kg POBD FU for 11 LCA study references [37,39,40,42,43,45,47,49–52,57].

[37,39,42,43,47,49,51,52], as they have all five parameters: EFB, Fibres, Shells, Kernel and CPO. However, Achten *et al.* [40] was the most incomplete data set, with only CPO, Fibres and Shells data. This is a direct reflection on the individual studies' methodological choices and without other Cameroon studies in this analysis there was no additional data to fill in data set gaps with. Papong *et al.* [50] is also incomplete, as kernel data was not present in their study, also due to individual methodical choices. The most interesting study in Fig. 8 is Wicke *et al.* [45], as despite having average results for FFB and CPO processing in Figs. 4 and 5, it has the greatest level of discrepancy for FFB mass contribution.

This diversity in data completeness for all stages of LCA demonstrates how important it is to ensure that all data fields, if not as many as possible, are fully represented in an LCA, so that inconsistencies and data discrepancies are avoided. When using existing studies, care should be taken to evaluate the depth of data shown and how transparent the studies are.

The final area of analysis is on the data sets themselves. Variance analysis was performed to demonstrate the extent of data variation for each parameter (Figs. 9–11). Parameters showing thinner black bars demonstrate data with no or little variation between studies, such as the amount of CPO needed. The zero error for the POBD was because this was a pre-determined fixed point for this analysis). The vertical lines protruding from the boxes represent the range between the highest and lowest values. The boxes themselves represent the ranges between the median and average values, pale boxes have averages below the median, dark boxes have averages above the median. A set of consistent data sets would have a majority of the parameters having little difference between average and median and low variance, if any.

Fig. 9 shows variances between the quantity data for FFB having the

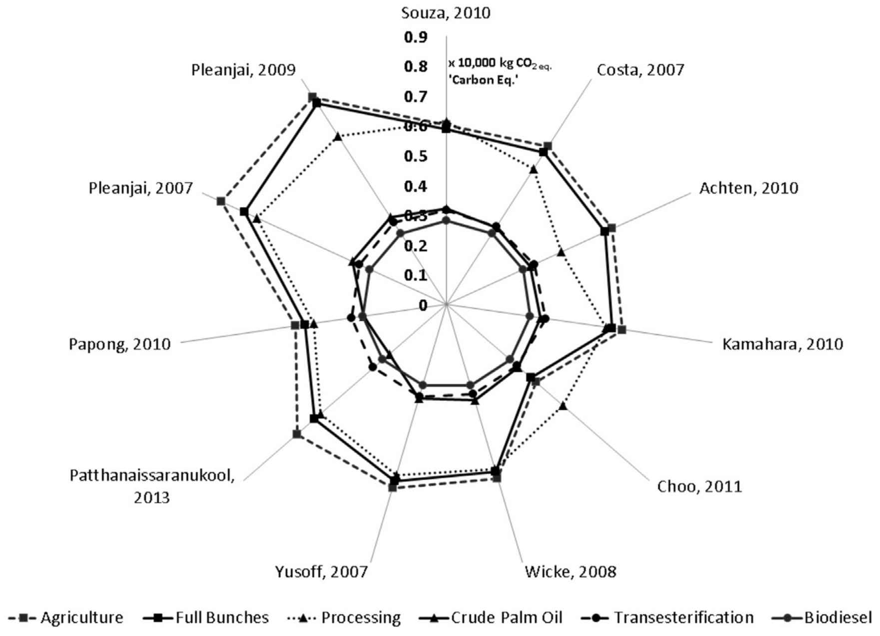

Fig. 7. Carbon equivalence data variations for 1000 kg POBD FU for 11 LCA study references [37,39,40,42,43,45,47,49–52,57].

Table 2
Normalised Life Cycle Inventory: quantity, energy, and carbon data with medians and co-efficient variation bandwidths [37,39,40,42,43,45,47,49–52,57].

Fresh Fruit Bunches	*Quantity (kg)*			*Coefficients of Variation*	*Energy Eq. (MJ $_{eq.}$)*			*Coefficients of Variation*	*Carbon Eq. (kg $CO_{2\,eq.}$)*			*Coefficients of Variation*
	Median	**Min**	**Max**	**(%)**	**Median**	**Min**	**Max**	**(%)**	**Median**	**Min**	**Max**	**(%)**
Fertilisers												
N	154.8	7.1	302.5	95	7513.5	234.7	14,792.3	97	188.8	8.6	369.1	95
P	42.4	0.4	84.5	99	739.5	6.1	1472.8	99	51.8	0.4	103.1	99
K	126.2	37.3	215.0	70	1178.1	124.6	2231.7	89	153.9	45.5	262.3	70
Mg	33.1	2.9	63.3	91	618.8	54.2	1183.4	91	40.4	3.5	77.2	91
B	37.5	0.4	74.6	99	1571.0	18.2	3123.9	99	45.8	0.5	91.0	99
Total	**394.0**	**48.1**	**739.9**	**88**	**11,620.9**	**437.8**	**22,804.0**	**96**	**480.6**	**58.6**	**902.7**	**88**
Herbicide	1.1	0.0	2.2	100	248.7	0.1	497.2	100	11.4	0.0	22.9	100
Diesel	10.2	1.7	18.8	84	538.7	60.3	1017.1	89	29.9	19.6	40.1	34
Water	8250.0	8250.0	8250.0	0								
Full Bunches	5123.6	3255.0	6992.2	36	78,040.0	52,080.0	104,000.0	33	5880.7	3736.0	8025.4	36
Crude Palm Oil	*Quantity (kg)*			*Coefficients of Variation*	*Energy Eq. (MJ $_{eq.}$)*			*Coefficients of Variation*	*Carbon Eq. (kg $CO_{2\,eq.}$)*			*Coefficients of Variation*
	Median	**Min**	**Max**	**(%)**	**Median**	**Min**	**Max**	**(%)**	**Median**	**Min**	**Max**	**(%)**
Full Bunches	5123.6	3255.0	6992.2	36	78,040.0	52,080.0	104,000.0	33	5880.7	3736.0	8025.4	36
Boiler Water	2737.5	1575.0	3900.0	42								
Steam	5.3	4.2	6.5	22	6423.3	2537.6	10,309.0	60				
Electricity (kWh)	534.4	9.7	1059.2	98	1924.0	34.9	3813.1	98	61.9	6.2	836.8	1251
Diesel	5.6	1.9	9.2	66	251.7	106.0	397.3	58	18.4	7.8	29.0	58
Empty Bunches	1127.2	716.1	1538.3	36	8205.9	5213.2	11,198.7	36	805.6	511.8	1099.4	36
POME	1837.5	1553.5	2121.6	15	305.0	257.9	352.2	15	35.6	30.1	41.1	15
Fibres	666.1	423.2	909.0	36	8205.9	5213.2	11,198.7	36	719.8	457.3	982.3	36
Shells	281.8	179.0	384.6	36	4382.0	2783.8	5980.1	36	379.1	240.9	517.4	36
Kernel	230.0	29.5	430.5	87	4266.8	547.8	7985.8	87				
Biogas	45.3	28.8	62.0	37	1042.3	663.3	1424.9	37	227.1	144.5	310.5	37
Crude Palm Oil	987.9	835.2	1140.6	15	38,121.6	34,040.0	42,203.1	11	3006.9	2542.1	3471.6	15
Biodiesel	*Quantity (kg)*			*Coefficients of Variation*	*Energy Eq. (MJ $_{eq.}$)*			*Coefficients of Variation*	*Carbon Eq. (kg $CO_{2\,eq.}$)*			*Coefficients of Variation*
	Median	**Min**	**Max**	**(%)**	**Median**	**Min**	**Max**	**(%)**	**Median**	**Min**	**Max**	**(%)**
Crude Palm Oil	987.9	835.2	1140.6	15	38,121.6	34,040.0	42,203.1	11	3006.9	2542.1	3471.6	15
Water	250.9	145.3	356.4	42								
Electricity (KWh)	156.2	5.0	307.4	97	554.3	1.8	1106.7	100	97.8	0.3	195.3	100
Methanol	136.8	93.2	180.5	32	4423.9	2062.3	6785.6	53	156.8	73.6	240.0	53
Sodium Hydroxide	6.0	2.0	10.0	67	157.4	52.6	262.3	67	4.7	1.6	7.9	67
Wastewater	250.9	145.3	356.4	42								
Glycerol	156.3	102.6	210.0	34	8815.3	5786.6	11,844.0	34	228.8	157.3	300.3	31
Biodiesel	1000.0	1000.0	1000.0	0	39,600.0	39,600.0	39,600.0	0	2823.0	2823.0	2823.0	0

largest variation, followed by boiler water in the central processing stage. The extent of the FFB data variance emphasises the wide range between data sets. Whereas in Fig. 10, the greatest variance is still the FFB, with nitrogen fertiliser also having ranges in energy equivalence data; this trend in FFB is also true in Fig. 11.

Some fields are missing across all the data sets for energy and carbon equivalence values, which do not have bars or values. As previously stated, these omissions could be due to the limitations of the study data sets in terms of completeness, but they could also be due to differences in geography and/or plantation/industrial process

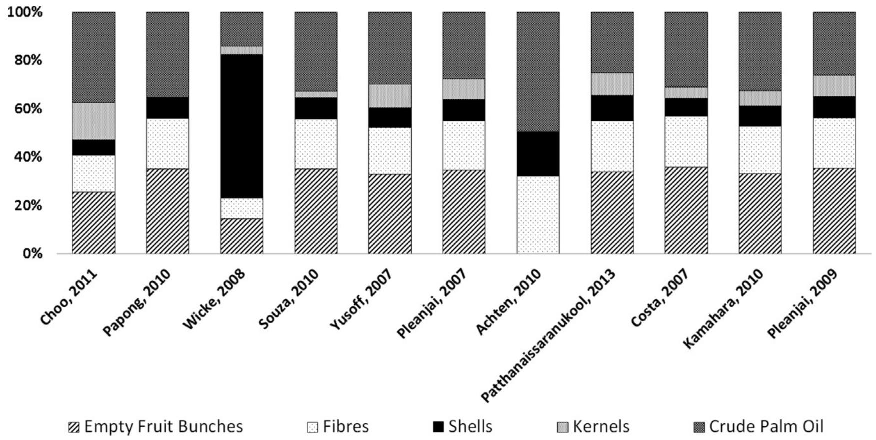

Fig. 8. Percentage mass contribution of FFB components for 11 LCA study references [37,39,40,42,43,45,47,49–52,57].

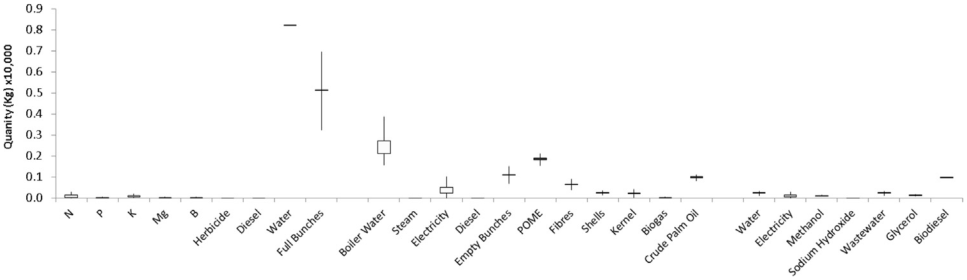

Fig. 9. Quantity data set parameter co-efficient variations for 1000 kg POBD FU for 11 LCA studies [37,39,40,42,43,45,47,49–52,57].

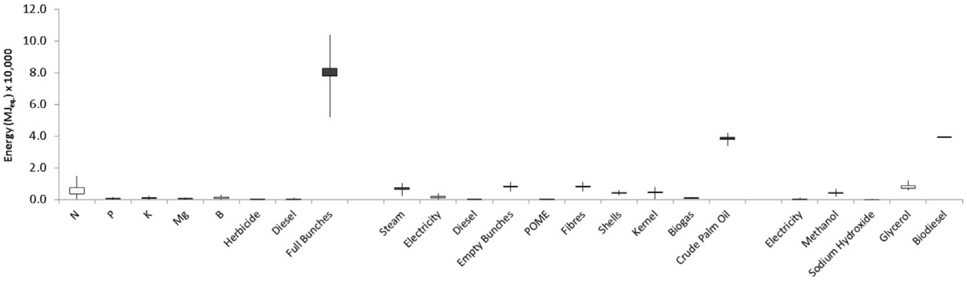

Fig. 10. Energy equivalence data set parameter co-efficient variations for 1000 kg POBD FU for 11 LCA studies [37,39,40,42,43,45,47,49–52,57].

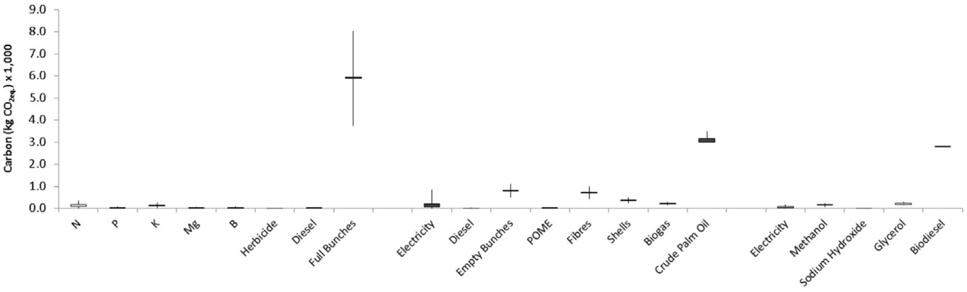

Fig. 11. Carbon equivalence data set parameter co-efficient variations for 1000 kg POBD for 11 LCA studies [37,39,40,42,43,45,47,49–52,57].

variations. Improvements for this data analysis would be to fill in the missing slots with data acquired from generic process information or derived from similar geographical sources, as previously stated, so that all parameters are populated.

In regards to practical assessment of parameter variations in this research field, the majority of impact comes from techno-economic reports, which cover a variety of inputs and outputs – especially costs. These report emphasise the importance of including parameter uncertainties, as not doing so can produce misleading results [58]. They also find engineering inevitabilities, which are common across developing countries, cause technological uncertainties. These can result in higher prices for biodiesel production and feedstock and instability in the market [59,60]. Crude palm oil is the most influencing parameter in biodiesel production [58,61], so when newer papers don't include them in their data sets, it is also increasing the uncertainty in the LCA field. Much like the variations between the LCI's investigated in this chapter, by not discussing them and producing an LCI from only two or three papers, or even missing out parameters altogether, can also have the potential of misrepresentation.

4. Discussion

Many studies of similar geographic origin had similar data, which in turn varied in comparison to other geographies, as demonstrated in Figs. 3, 6 and 7. Therefore special attention has to be given that studies of similar geographical origin are used in comparisons. In contrast, a major source of variation between studies arose from methodological differences. The specificity of data collection and system boundaries was by far the largest contributor, as studies with higher percentages of original data e.g. both Pleanjai *et al.* [51,52] studies were found to be more accurate than those with high levels of synthesised data e.g. Achten *et al.* [40]. The degree of homogenisation also impacted on the accuracy of data, as studies with POBD FUs were not influenced as much as those with CPO FUs.

In summary, the flexibility of the ISO 14040 and 14044 standards in offering a practitioner a choice in setting the study parameters inevitably means that the individual configurations of different studies on similar or the same products – in this case POBD – will necessarily lead to some diversity in results. It is therefore mandatory to evaluate carefully the relevance of a given study to the LCA question(s) being asked and, as we have done here, ideally to assimilate data and results from several relevant studies (including additional bridging of any data gaps *etc*. where needed) in order to obtain an appropriate and generic perspective on the LCA evidence.

This study provides support to the increased interest in biomass research on fuels for the transport sector. There is a current lack of use of reliable LCA research in this area. The study is intended to contribute to evaluating the variations occurring across selected POBD LCA studies, to help others find more reliable studies. One example being that studies with either lesser or greater data set completeness, amongst other factors, can greatly influence the overall results.

5. Conclusions

This study presents a novel, 11 study comparison and data set formation for product, energy, and carbon equivalent values for the ‘Well to Tank’ assessment of POBD.

As part of the in-depth exploration of variation between different LCA's of palm oil biodiesel (POBD), this study has assembled a comparison inventory of quantities, energy, and carbon equivalence analyses for the production of POBD and its co-products. The process of aligning LCA data from several publications and other sources revealed substantial heterogeneity in the reporting of system boundaries, methodological approaches, and basic data between studies. An FU of production of 1000 kg POBD was utilised to scale the reported inputs, outputs and environmental impacts to derive representative and well characterised generic values and data ranges.

Biodiesel is an important step towards the market introduction of renewable transport fuels and it is essential that its environmental performance is reliably evaluated through internationally recognised methods such as LCA. The present study demonstrates that variation between LCA studies in aspects such as system boundaries, geography, and other details such as parameter choices occurs but by use of careful processes for data and results evaluation, filtering and assimilation, these can be accommodated in compiling an appropriate generic inventory assessment for POBD.

Acknowledgments and funding

The research in this paper was produced as part of a PhD funded by the Doctoral Training Centre in Hydrogen, Fuel Cells and their Applications (EP/G037116/1) led by the University of Birmingham. We gratefully acknowledge the support by EPSRC and the University of Birmingham for this research.

Conflicts of interest

none.

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