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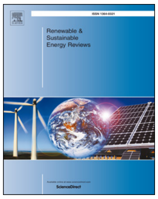

Methodological analysis of palm oil biodiesel life cycle studies

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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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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

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