# Critical Parameters in The Life Cycle Inventory of Palm Oil Mill Residues Composting

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**Abstract**

The environmental impact of palm oil production is a global concern that has been scrutinized by the scientific community. Co-composting palm oil mill by-products (empty fruit bunch – EFB and palm oil mill effluent – POME) has been promoted as an efficient way to reduce environmental footprint. Co-composting as a sub-system in the life cycle of crude palm oil (CPO) has a direct impact on the value of four critical parameters: anaerobic degradation of organic matter (methane emissions), use of inorganic fertilizer, net amount of waste and overall fuel consumption. However, those theoretical benefits are mostly quantified from life cycle assessment models that rely on non-specific data sets and optimistic modeling assumptions. This paper compares data from a case study in a palm oil agro-industry to life cycle inventories found in the literature. Different composting processes were tested on site. Recycled biomass and effluents, energy and water demand, compost quantity and quality, fertilizer consumption and yields were recorded over a year. Results showed some significant differences with existing models. Composting led to a 35% reduction of global warming potential (GWP) compared to sole anaerobic digestion of POME, against 88-95% in the literature. We showed that the result of the greenhouse gas (GHG) balance is very sensitive to the emission factor chosen and the value used for chemical oxygen demand (COD) in the effluents. The use of compost in the plantation replaced 10% of inorganic fertilizer against 25% in modeling assumptions. Those differences in critical parameters can be linked to seven critical practices to be integrated in the models for better life cycle inventories: i) the POME/FFB ratio from the mill ii) the pre-treatment of POME iii) the roofing of the composting platform, iv) the POME/EFB ratio, v) the turning frequency, vi) the recycling of leachates and vii) the process duration and drying period.

**Keywords:** *Palm Oil; Life Cycle Inventory; Compost; EFB; POME*

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## 1 INTRODUCTION

Over the last decades, palm oil has become an unavoidable commodity. It has taken a growing part in the diet of most countries and became the world's most consumed edible oil fifteen years ago [1]. But besides feeding the world's population, palm oil has caused a vivid controversy over its environmental and social impact [2]. In Indonesia, the world leader in palm oil production, high losses of biodiversity and significant greenhouse gas (GHG) emissions are reported because of land clearing and fires, especially on peatlands [3] [4].

As the debate is focused on the issues of land use change and biodiversity conservation, the agricultural practices themselves are often overlooked. Oil palm plantations, as every crop, will have a different impact on their local and distant environment depending on the way they are managed. Therefore, the question is how to minimize environmental impact in existing plantations [5]. More specifically, what practices shall be promoted, and according to which criteria. In this perspective, composting allows recycling organic residues and partly replaces imported chemical fertilizers in the field. However, the composting process itself may also directly impact the environment. There is a need to assess potential trade-offs within the system considering the impacts both in the field and at the mill stage.

Life Cycle Assessment (LCA) is an international reference in terms of supply chain environmental analysis. It consists of 4 steps relevant to evaluate the potential benefits and trade-offs of such a waste-management system. First, the goal and scope step consists in defining the system boundaries and subsequent study assumptions. Second, the life cycle inventory (LCI) quantifies all inputs and outputs from processes within the system, and derived emissions to the environment. Third, the life cycle impact assessment (LCIA) is done using causal models to link emissions from the LCI to environmental mid-point impact categories (e.g. human toxicity or global warming potential), and up to end-point impact categories (e.g. human health) in some LCIA methods. Such end-point impact indicators provide more aggregated information useful for decision making [6]. The last ISO norm step in LCA methodology is the result interpretation, which requires a comprehensive understanding of all assumptions made in the previous steps.

The objective of this study is to provide key information on the critical parameters for a comprehensive accounting of palm oil mill compost in LCI. In the first section, we reviewed the literature on composting with an overview of composting occurrence in LCA and a focus on palm oil mill compost. In the second and third sections, we investigated the influence of critical compost parameters, as identified in the review, thanks to a case study and a dedicated composting trial.

## 2 LITERATURE REVIEW

### *2.1 What is composting?*

Composting is a complex biological transformation of organic matter carried out by a succession of microbial communities under controlled environmental conditions. Several definitions of composting can be found in the scientific literature, each author stressing a different aspect of composting such as the succession of microbial communities [7] [8] [9], the physical conditions in which the degradation occurs , the control of the process [10], the gaseous emissions from compost [11] [12], or the end product itself [13]. Other authors focus on the maturity of compost [14], its mineralization kinetics and its potential for increasing soil organic carbon stock [15].

The composting process occurs in the solid state and is mostly aerobic. The three main transformations occurring during composting are: i) degradation of organic matter through microbial respiration, ii) production of metabolic water and a loss of water through biological drying and iii) stabilization of organic matter with the production of humus like substances. Composting leads to a loss of organic matter in the form of volatile compounds such as $CO_2$, $CH_4$, $N_2O$, $NH_3$, $N_2$, and volatile $H_2O$ [16] [17] [11]. Longer composting processes lead to the production of more stable compost with a high potential for increasing soil organic carbon [18].

We can identify four successive phases in composting. First, the mesophilic phase occurs at the beginning of composting. The microbial degradation of the easily degradable organic matter causes an increase in temperature leading to the thermophilic peak (temperature above 55°C). Second, the thermophilic phase is where organic matter degradation and volatile emissions are the highest. Three, the cooling phase is when the temperature of compost slowly decreases below 40-45°C, a temperature at which lignin decomposers and nitrifying bacterium can develop. Four, the compost maturation is a phase during which the transformation of organic matter occurs at a slow rate, with a low respiration and a temperature close to ambient temperature.

### 2.2 The life cycle assessment of compost

LCA can inform decision making regarding treatment and recovery options for waste management, identifying and quantifying both positive and negative externalities. The implementation of the LCA approach for composting systems has previously been discussed in literature reviews [19] and case studies [20] [21]. The LCA results for composting units depend on the original feed stock used for composting, the composting system and the transportation for feedstock collection and compost application [19]. A sensitivity analysis [20] showed that electricity and fuel consumption for compost production and transport are hotspots for ozone depletion, carcinogenic, non-carcinogenic, and smog formation. Gaseous emissions during the composting process were critical for global warming, acidification and eutrophication. $CO_2$ emissions from the compost pile are biogenic and therefore always considered neutral whereas biogenic $CH_4$ emissions are not neutral because CH4 global warming potential is higher than that of $CO_2$. Impacting gaseous emissions come from biogenic $CH_4$ and $N_2O$, two gazes with a high GWP. Emissions and global GHG balance can vary greatly depending on the type of composting process [22] [23].

In terms of system boundaries, life cycle inventory of compost has to be expanded to post-application effects to account for benefits such as avoided use of inorganic fertilizers, higher water holding capacity, increased carbon storage, reduction of erosion and reduction of nutrient leaching [19]. Composting must also be considered in terms of net energy balance when compared to other waste management options [21].

### 2.3 Waste management and composting in the life cycle of palm oil

Besides the land use change impact, the main sources of environmental impact from palm oil production on mineral soils are the treatment of Palm Oil Mill Effluent [POME] in the mill, the use of nitrogen fertilizers in the plantation and traction energy for transport in the plantation [24] [25] [26] [27]. Those hotspots have a high contribution to global warming [27], fossil fuels depletion, and acidification/eutrophication [26]. The manufacture and transport of synthetic nitrogen fertilizer require large amounts of fossil energy [19] and can lead to high emissions of $N_2O$ and $NH_3$ as well as leaching/eutrophication [28] or soil degradation [29]. POME is by far the most problematic mill by-product, because of the large volumes of fermentable effluent with high moisture. In the past palm oil industries were criticized and sanctioned for discharge of raw or partially treated POME in water streams [2] [30]. Nowadays most of the mills perform partial anaerobic treatment in ponds or methanization in anaerobic digester tank, followed by field application of the treated POME. However this practice requires a careful management of field applications to avoid soil clogging and POME percolation in adjacent water bodies [31] and generates high methane emissions in the case of open ponds treatment [24] [25]. Compared to processing POME in anaerobic ponds, co-composting POME and EFB in aerobic conditions would significantly reduce methane emissions [32] [33] [34] [35]. Reduced methane emissions through co-composting or methane capture is a critical parameter for a carbon neutral palm oil [24] [27] [32] [33]. Compost is applied in the field as a substitute for mineral N-P-K-Mg fertilizers, and will therefore decrease fossil fuel consumption and other negative externalities of inorganic fertilization [27]. Further emission avoidance and a better net energy ratio can also be achieved if POME is pre-treated in a continuous anaerobic digester for producing biogas (methane) before using the bio-digester sludge for making compost [32] [33] [34] [36].

Compost presents other benefit such as mid-term and long term storage of carbon, improved soil quality and protection from soil erosion [19] [37] [38]. The effect of compost on field emissions and soil quality has not been included yet in LCA models for fresh fruit bunch (FFB) production due to a lack of reliable data.

### 2.4 Variations in the composting process

The composting process of palm oil by-products has been investigated in a large number of scientific studies published in peer review journals or conference proceedings. We have considered 15 of those publications to provide a background to this study [7] [39] [40] [41] [42] [43] [44] [45] [46] [47] [48]. According to the extraction process used in the mill, various co-products can be available for composting in oil palm industrial areas: empty fruit bunches (EFB), palm oil mill effluent (POME), solid decanter cake, mesocarp fibers and boiler ashes. The two most important by-products in terms of quantity are POME and EFB. EFB are produced at a ratio of 0.2-0.23 t EFB/t FFB (“t” stands for metric ton). The amount and the composition of POME can vary from 0.25 $m^3$ to 0.65 $m^3$/t FFB [48]. There are several composting processes existing within palm oil plantations (open windrows, covered windrows, roofed platform, bunker, on bare soil or concrete floor). We summarized the various factors that could influence the kinetics of composting and the final quality of compost:

- The amount of POME (POME/EFB ratio)
- The quality of POME (Raw vs. Predigested)
- Pre-treatment of EFB (shredding, chopping)
- Addition of microbial inoculum
- Addition of urea
- Addition of solid decanter cake
- The size and the shapes of the compost piles
- Covering the compost piles
- The frequency of spraying and turning
- Using passive or forced aeration of piles
- Recycling of POME leachates
- Drying-maturation period
- Duration of the process

The composting processes in those studies ranged from 28 to 120 days, with a turning frequency ranging from every 2 days to every 40 days and a POME/EFB ratio ranging from 0.35 to 6.5 $m^3$/ton. Moisture and aeration are of paramount importance in the early stage of the composting process. The median values for turning intervals were 3-7 days and most of the studies focused on POME/EFB ratios from 1 to 3. The final dry weight reduction was 40 to 60% after 120 days [46]. The EFB have a very high initial carbon to nitrogen (C/N) ratio, not optimal for composting. Composting will be accelerated by adding nitrogen (N) in the form of urea [46] or solid decanter cake with high N content [51]. In most of the studies considered, EFB were pretreated (shredded or chopped). The composition of EFB (Table 1) is quite constant throughout the literature. Chemical properties of effluents (Table 2) have a wider variations range, depending on pretreatments before composting (methane production in bio-digester, filtration, cooling and sedimentation, digestion in aerobic or anaerobic ponds). The composting kinetics as well as the nutrient content of the end-product will therefore vary according to the type of POME used. Using pre-digested anaerobic sludge instead of raw POME will help to lower the C/N ratio of the mix and reach quicker compost stability [41]. The nutrient content of the compost that will be applied in the field varies greatly according to the composting system and the duration of the process (Table 3). Some compost are very rich in nutrients, with N > 3% and K > 5%, but most compost have a nutrient content below or equal to EFB for K and N, suggesting losses during the composting process.

Only one study quantified the losses in nutrients during composting [46]. It showed that with an open composting system almost 50% of the phosphorus (P), 70% of the potassium (K), 45% of the magnesium (Mg) and between 10%-20% of the calcium (Ca) initially contained in the EFB and POME were lost after 10 weeks of composting. Those losses were explained by an open window system, subject to important rainfalls and without the recycling leachates from the compost. The study stressed the importance of protecting the windrows from rainfalls to minimize losses. It also suggested that a spraying interval of three days was not optimal, because a lot of POME is sprayed on the piles at once and is not absorbed properly.

**Table 1.** Composition of EFB (literature review)

| Source | Pre-treatment | Moisture% | pH | C/N | C %DM | N %DM | P %DM | K %DM | Ca %DM | Mg %DM |
|---|---|---|---|---|---|---|---|---|---|---|
| Baharuddin *et al*, 2010 | Press shredded | 29 | 6.9 | 54 | 43.49 | 0.8 | 0.08 | 2.01 | 0.26 | 0.12 |
| Abu Zharim & Asis, 2010 | Non shredded | 61 | - | - | - | 1.15 | 0.66 | 2.11 | | 0.27 |
| Baharuddin *et al*, 2009 | Shredded | 24 | 6.7 | 58 | 53 | 0.9 | 0.6 | 2.40 | 0.6 | 0.6 |
| Baharuddin *et al*, 2009 | Shredded | 25 | 6.5 | 56 | - | - | - | - | - | - |
| Thambirajah *et al*, 1995 | Shredded | - | 6.5 | 52 | 45 | 0.85 | - | - | - | - |
| Yahya *et al*, 2010 | Dried | 14 | - | 63 | 54.76 | 0.86 | 0.07 | 1.99 | 0.09 | 0.13 |
| Schuchardt *et al*, 2002 | - | 68 | 7 | 57 | 48.5 | 0.86 | 0.06 | 2.09 | 0.28 | 0.14 |
| Saletès *et al*, 2004 | Shredded | 60 | | 40 | 49.6 | 1.25 | 0.11 | 2.07 | 0.42 | 0.2 |
| **Average** | | 40 | **6.72** | **54.71** | **49.06** | **0.95** | **0.27** | **2.11** | **0.33** | **0.24** |

### *2.5 Agronomical quality of compost*

The efficiency of the composting process must also be assessed in light of the compost quality when applied in the field, i.e. from an agronomical point of view. A study showed that 10 t/ha (70 kg/palm tree/year) of compost can be used as a substitute for mineral fertilizers regarding N and P nutrition, in mature oil palm plantations [54]. Trials also showed that compost application could increase soil pH and exchangeable cations and organic matter on a short term basis [55]. The results are encouraging but would need to be confirmed by other studies. A trial showed that 7.5 kg of compost mixed with usual topsoil in polybags can replace mineral fertilization in nursery and would improve soil chemical properties [56].

The use of compost as a fertilizer in palm oil plantation lacks further documentation but several other studies documented the effect of organic matter application in the form of fresh EFB. Carron *et al* [57] showed that EFB application would increase soil fertility and biological diversity for at least two years after application. Tao *et al* [58] found that EFB application increased soil microbial activity. Compost could have the same effect as EFB with lower cost of application (reduced volume and weight), a higher content in nutrients and a higher potential for increasing soil organic carbon.

**Table 2.** Composition of various types of POME (literature review). Raw POME corresponds to effluent coming directly from the plant after the extraction of palm oil. Anaerobic sludge is POME that already underwent treatment in an anaerobic digester

| Source | POME | Water % | pH | COD mg/L | C/N | C mg/L | N mg/L | P mg/L | K mg/L | Ca mg/L | Mg mg/L | S mg/L |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Schuchardt *et al*, 2000 | Raw | - | 4.6 | - | - | - | 270 | 22 | 393 | 145 | 82 | - |
| Schuchardt *et al*, 2002 | Raw | - | 4.3 | - | - | - | 600 | 110 | 1500 | 300 | 280 | - |
| Baharuddin *et al*, 2010 | Raw | 98 | 4.33 | 113 190 | 13 | 6510 | 485 | 181 | 446 | 279 | 217 | 102 |
| Baharuddin *et al*, 2010 | Anaerobic sludge | 94 | 7.41 | 40 560 | 8 | 22 390 | 2794 | 746 | 3080 | 1522 | 842 | 722 |
| Abu Zharim & Asis, 2010 | Raw | 96 | - | - | - | - | 32 | 13,76 | 398 | 1020 | 360 | 484 |
| Baharuddin *et al*, 2009 | Anaerobic sludge | 95 | 7.5 | - | 8 | 9500 | 1150 | 650 | 1000 | 250 | 500 | 350 |
| Salètes *et al*,2004 | Anaerobic sludge | - | 6.6 | - | - | - | 450 | 310 | 2090 | 380 | 545 | - |
| Ahmad *et al*, 2011 | Anaerobic sludge | 95 | 7.4 | 40 560 | 8 | 14950 | 1794 | 552 | 920 | 736 | 414 | 2116 |

**Table 3.** Composition of various palm oil mill composts (literature review)

| Source | Age (days) | Water % | pH | C/N | C %DM | N %DM | P %DM | K %DM | Ca %DM | Mg %DM |
|---|---|---|---|---|---|---|---|---|---|---|
| Baharuddin *et al*, 2010 | 40 | 51 | 8.12 | 12 | 28.81 | 2.31 | 1.36 | 2.84 | 1.04 | 0.90 |
| Abu Zharim & Asis, 2010 | 30 | - | 8.20 | 20 | - | 1.70 | 0.22 | 1.41 | - | 0.48 |
| Abu Zharim & Asis, 2010 | 150 | - | 8.00 | 23 | - | 1.90 | 0.34 | 1.66 | - | 0.48 |
| Baharuddin *et al*, 2009 | 60 | 61 | 8.10 | 13 | 28.00 | 2.20 | 1.30 | 2.80 | 0.70 | 1.00 |
| Baharuddin *et al*, 2009 | 60 | 60 | 7.80 | 13 | - | - | - | - | - | - |
| Thambirajah *et al*, 1995 | 60 | - | 9.00 | 14 | 37.50 | 2.65 | - | - | - | - |
| Thambirajah *et al*, 1995 | 60 | - | 9.00 | 18 | 36.00 | 1.90 | - | - | - | - |
| Thambirajah *et al*, 1995 | 60 | - | 9.00 | 12 | 27.00 | 2.20 | - | - | - | - |
| Yahya *et al*, 2010 | 51 | 53 | 8.50 | 18 | 47.40 | 2.50 | 0.51 | 2.40 | 0.83 | 0.48 |
| Yahya *et al*, 2010 | 51 | 53 | 8.60 | 28 | 48.60 | 1.70 | 0.43 | 2.04 | 0.67 | 0.48 |
| Schuchardt *et al*, 2002 | 70 | 16 | 7.50 | 15 | 35.10 | 2.34 | 0.31 | 5.53 | 1.46 | 0.96 |
| Saletès *et al*, 2004 | 70 | 42 | - | 14 | 41.60 | 2.86 | 0.34 | 2.30 | 1.27 | 0.63 |
| Saletès *et al*, 2004 | 70 | 42 | - | - | 41.50 | 3.25 | 0.35 | 2.01 | 1.37 | 0.76 |
| Saletès *et al*, 2004 | 70 | 42 | - | - | 42.30 | 2.96 | 0.34 | 2.32 | 1.28 | 0.70 |
| Saletès *et al*, 2004 | 70 | 42 | - | - | 41.70 | 3.13 | 0.34 | 2.08 | 1.34 | 0.70 |

### *2.6 Conclusion from the literature review*

The current state of scientific knowledge is that co-composting EFB and POME is highly beneficial from an environmental perspective. 5 parameters are critical to quantify the costs and benefits of compost in LCI: 1) Energy consumption: making compost requires energy (electricity and diesel fuel) 2) Methane avoidance: anaerobic digestion of POME is avoided 3) Waste reduction: the net amount of waste to be returned to the field is reduced by composting 4) Nutrient recovery: nutrients recovered in the compost replace imported fertilizers 5) Improved soil quality: compost application enhances nutrition efficiency, soil biodiversity and ecosystem services.

The existing LCA models do not integrate parameter n°5, which is often very difficult to quantify. They derive parameter 1 to 4 from modeling assumptions, but do not discuss nor analyze variability in existing composting systems. The aim of this study is to provide site-specific data for the first 4 critical parameters listed above and compare it to existing LCI assumptions. We also aim at shedding some light on the variation range of those parameters by identifying key composting practices in the mill.

## 3 METHODS

In order to investigate composting critical parameters, we gathered data from an industrial mill and its supply basis as well as from a dedicated composting trial. The data collection and the analysis approach are detailed in this section.

### *3.1 System boundary and functional unit*

The system considered is the palm oil mill gate-to-gate system, receiving FFB from the plantation to produce crude palm oil (CPO) that is defined as the main functional unit, i.e. 1 t CPO at the mill gate. In this mill gate-to-gate system, we did not account for the plantation stage impacts. FFB from the plantations were considered as input flows to the mill without embedded environmental burden.

The study did not aim at carrying out a comprehensive inventory but focuses on the compost with 4 parameters identified as potential impact "hotspots"; energy, GHG emissions, net waste in the mill and displaced inorganic fertilizers. Such substitution is usually covered in LCA through system expansion. In this preliminary study, though, the displaced inorganic fertilizers were investigated only in terms of nutrient recovery efficiency, i.e. in terms of nutrient equivalents. As we did not include the plantation stage, we did not account for avoided emissions due to system expansion in the GHG balance calculations for the compost.

### *3.2 Industrial case study*

*CPO production and by-product output*

We collected data from one mill receiving FFB from 13,816 ha of oil palm (*Elaeis guineensis Jacq.*) in the province Central Kalimantan, Indonesia. 90% of the area was planted between 2006 and 2009, and the remaining 10% between 2010 and 2014. The precedent land use was a mix of forest, shrubs and a mix agricultural land. All of the land was planted with high-yielding Tenera hybrids. In 2017, the production was 272,929 t FFB, with an average yield of 19.8 t FFB/ha/year (all ages combined). The CPO production was 68,805 t with an average oil extraction rate of 25.21%. Shell and mesocarp fibers are entirely burnt to feed the mill's boiler. The overall yearly POME/FFB ratio was 61.6% with 168,142 $m^3$ of POME (Figure1 flowmeter 2) and the EFB/FFB ratio was 21.07% with 57,525 t EFB produced over the year. In collaboration with the mill and estate staff, we collected the following data for the year 2017:

- Overall yield and production of the plantation
- Energy and water consumption of the mill
- Fertilizers consumption (mineral and organic)
- Energy consumption of the composting platform
- Quantity and quality of the compost produced
- Quantity and quality of effluents produced.

*Composting platform*

In 2017, the composting platform (Figure 1) received all the EFB from the mill after shredding, which were transported in bins (capacity of 10 to 13 t of shredded EFB) carried by the prime mover. Two machines operated the platform: a loader and a mechanical compost turner (Backhus™) that was modified to combine spraying and turning. The composting platform received cooled raw POME from the mill (Table 4) that was stored in a temporary open pond (spraying pond: 1,250 $m^3$). They were then pumped to outlets located every two compost rows. Flexible pipes were connecting POME outlets to the turner.

The non-roofed concrete platform was surrounded by drains for collecting the leachates. All leachates (Table 5) were collected in the North East corner of the platform to a small run off pond (60 $m^3$) and then recirculated to a buffer pond (4,500 $m^3$). The leachates were pumped back to the different anaerobic effluents ponds that are 2-3 m deep. Final effluent after anaerobic treatment (Table 6) were applied in flatbeds in the oil palm plots surrounding the mill. The function of the anaerobic ponds was to decrease the chemical oxygen demand (COD) of the effluents below 5,000 mg/L so that they could be applied in the field. The composting platform received about 150,000 $m^3$ of rainfall (3,000 mm/year) in addition to the 168,000 $m^3$ of POME used for spraying compost (Figure1, flowmeter 3). It resulted in the leaching of 127,000 $m^3$ of effluent (flowmeter 4) from the composting platform to the anaerobic pond. Those ponds also received 16,000 $m^3$ of grey water from the mill (flowmeter 1). With the dilution by rainwater, the final amount of effluent sent to land application was 350,000 $m^3$ (flowmeter 5).

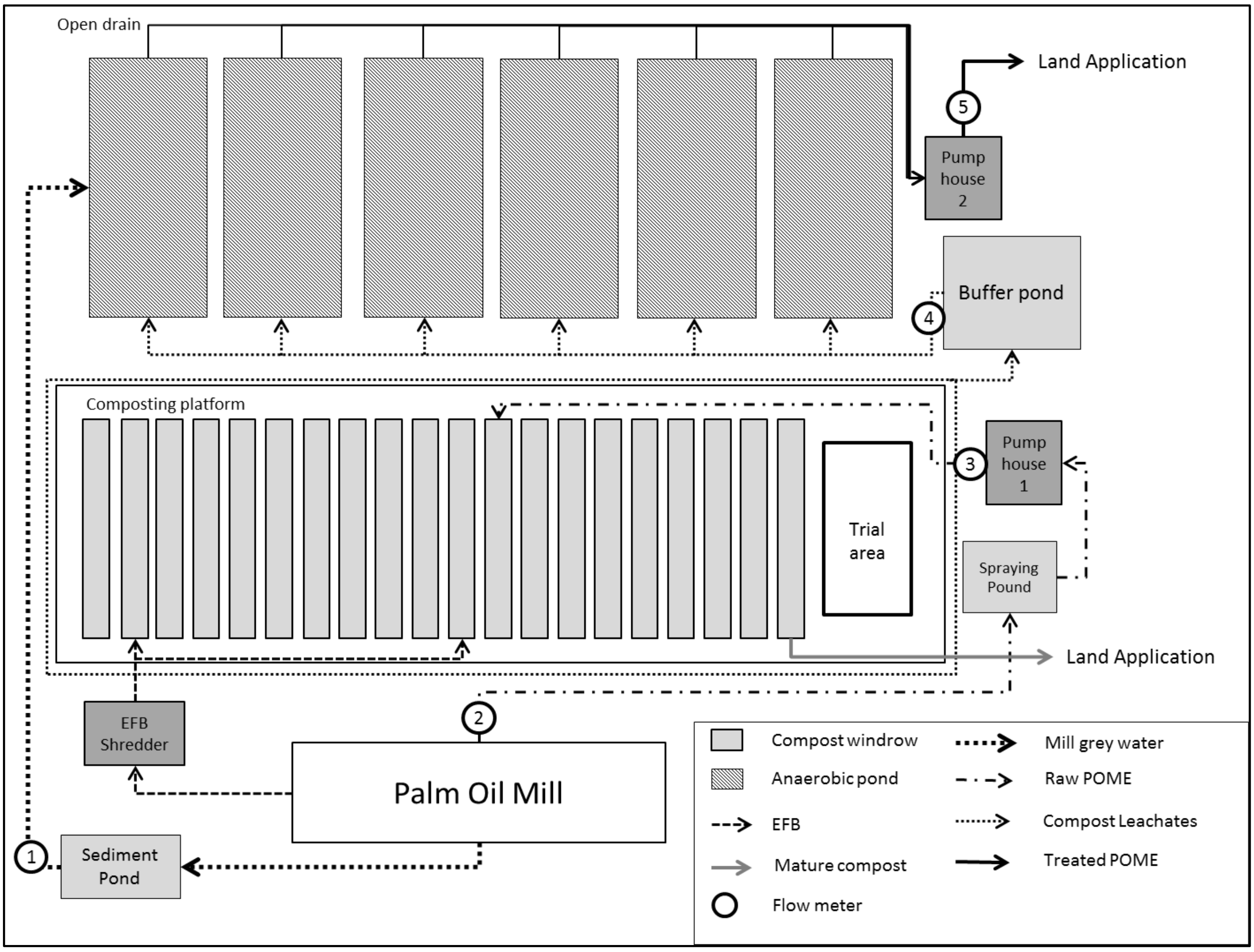


**Figure 1.** Waste management system in the mill. Numbers 1 to 5 indicate the location of flowmeter that were used to measure the flow of effluents at each treatment stage 1) Mill grey water 2) Hot raw POME 3) Cooled raw POME 4) Compost leachates 5) Treated effluent for land application

**Table 4.** Biochemical analysis of raw effluents (120 samples taken over 4 months in the pump house 1)

| | Total solid mg/L | $BOD_5$ mg/L | COD mg/L | N mg/L | P mg/L | K mg/L | Mg mg/L |
|---|---|---|---|---|---|---|---|
| **CI95 +** | 63,918 | 36,485 | 90,470 | 1,216 | 232 | 3,017 | 639 |
| **Average** | 61,180 | 34,337 | 87,242 | 1,166 | 224 | 2,912 | 617 |
| **CI95 -** | 58,443 | 32,189 | 84,013 | 1,117 | 217 | 2,807 | 595 |

**Table 5.** Biochemical analysis of compost leachates (25 samples taken over one month in the drains surrounding the platform)

| | $BOD_5$ mg/L | COD mg/L | N mg/L | P mg/L | K mg/L | Mg mg/L | Ca mg/L |
|---|---|---|---|---|---|---|---|
| **CI95 +** | 35,670 | 79,231 | 1,421 | 284 | 5,568 | 666 | 557 |
| **Average** | 28,384 | 70,370 | 1,298 | 256 | 4,321 | 600 | 482 |
| **CI95 -** | 21,098 | 61,509 | 1,175 | 227 | 3,074 | 534 | 408 |

**Table 6.** Biochemical analysis of final effluent sent to land application (average of 4 samples taken over 1 month)

| $BOD_5$ mg/L | COD mg/L | pH | Oil and fat mg/L | Pb mg/L | Cu mg/L | Cd mg/L | Zn mg/L |
|---|---|---|---|---|---|---|---|
| 1,748 | 5,985 | 7.6 | 352 | <0.0017 | <0.015 | <0.022 | 0.21 |

*Greenhouse gas balance of the compost*

The GHG balance was quantified per t CPO within the mill gate-to-gate system, i.e. without accounting for the plantation stage. Therefore, we did not take into account GHG emissions related to the application of compost in the field, nor did we consider any potential avoided emissions due to system expansion with substituted mineral fertilizers.

For the estimate of the GHG balance, we used primary data for the elementary flows concerning the amount of waste treated and compost produced, and the amount of fuel used by machines for the composting process. The GHG emission coefficient for the diesel burned was taken from IPCC.

We also relied on primary data on COD to calculate the amount of carbon decomposed during both pre-treatment and composting. Then we applied coefficients from the literature to estimate subsequent GHG emissions, as we could not implement GHG measurements on site. We followed equations from IPCC 2006 – Volume 5, Chapter 4 on waste water treatment, also used in the assessment of clean development mechanisms aimed at methane avoidance or methane recovery [59] [60] to derive GHG emissions based on COD removal.

Emissions embedded in capital goods, i.e., the construction of the mill, the composting platform, and the machines, were not included.

*Composting trial*

We implemented a trial on the composting platform in order to provide reliable data on the composting process, including all key parameters. The trial consisted in 30 piles of 10 t EFB that were regularly turned and sprayed with POME using the modified Backhus™ compost turner. The composting trial was part of the above-described industrial composting platform.

The trial was designed according to 3 different composting protocols existing within the PT. SMART Company (Table 7). The trial was also sub-divided to test the covering of the compost piles with semi-permeable tarpaulin.

**Table 7.** Experimental treatments

| Protocol | Additional Urea [2kg/t EFB] | Spraying and turning interval | Dose per spraying [L/t EFB] | Final POME/EFB ratio [$m^3$/t EFB] |
|---|---|---|---|---|
| **A** | No | 2 days | 100 | 2.9 |
| **B** | No | 1 day | 100 | 4.9 |
| **C** | Yes | 3 days | 200 | 3.1 |

The composting process theoretically lasts between 40 and 50 days in industrial conditions but the actual duration can vary according to vehicle availability to harvest and apply the compost. Our trial was extended to 72 days in order to see if extra maturation of the compost could be of importance in the LCI.

*Measurement protocol*

On the composting trial, we performed the following measurements:

- Temperature **(**2 measurement/day) at 9 measurement points (3 at the top, 3 at the middle and 3 at the base of the heaps).
- Moisture (2 measurement/day): A composite sample of compost was taken from each pile. Samples were dried in an oven at 105°C until constant weight was reached (12 to 24 hours).
- Weight (1 measurement/week): compost heaps are collected in a 10 t-capacity truck and transported to the mill weighing bridge. After weighing, compost is taken back to the platform and the heaps are reshaped.
- Composite samples for chemical analysis were taken once a week from each pile. Nitrogen content was measured with the Kjeldahl distillation method. Phosphorus was determined by acid-base method. Organic carbon was

determined by the gravimetric method. pH was determined through potentiometry.

*Nutrient recovery of the compost*

The nutrient recovery efficiency (NRE) is calculated for each element (N, P, K, Mg) as the ratio between the final stock of nutrient and the original stock of nutrient contained in the EFB and the POME, using the POME/EFB ratio of each protocol.

## 4 RESULTS

### *4.1 Energy consumption*

The overall energy and water consumption of the plant is presented in Table 8. Electricity used in the mill comes from a boiler using mesocarp fibers and shell as the main fuel. The energy surplus for composting was the electricity consumption of the EFB shredder. Diesel fuel was used to power vehicles, generators and pumps for handling the effluent. The surplus for composting was only from machines, pumps and vehicles operating in the composting platform. 83% of this surplus was consumed by the compost turner.

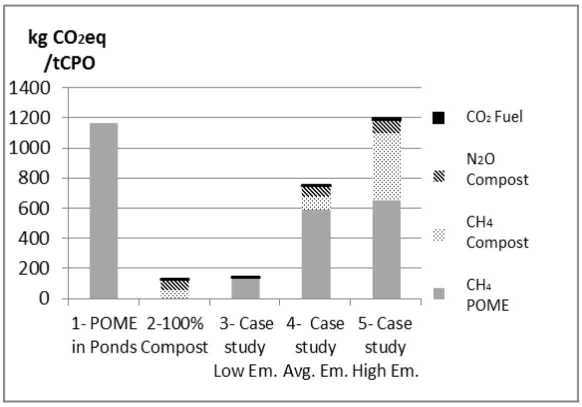


**Figure 2.** Different scenarios for GHG emissions from waste management in the mill

**Table 8.** Total Water and Energy consumed over a one-year period for producing CPO (Mill) and compost (Composting platform)

| | Total Mill | Compost Operation | Per t CPO | Increase due to compost |
|---|---|---|---|---|
| **Diesel Fuel (L)** | 422,032 | 105,175 | 8 | +25% |
| **Electricity (kWh)** | 5,137,296 | 526,454 | 82 | +10% |
| **Water ($m^3$)** | 266,743 | 6,809 | 4 | +3% |

### *4.2 Greenhouse gas emissions*

COD reduction is the standard unit to evaluate potential methane emissions from POME [59]. The average COD content of fresh POME was 87,000 mg/L, equivalent to a production of 0.213 t COD/t CPO, and the final COD content of effluent was 5,985 mg/L. Knowing the mass balance and COD of the effluents at the various stages, we could approximate a total COD removal during the waste management process. We could then allocate this removal to the composting platform (mostly aerobic conditions) and to the POME pond (mostly anaerobic condition). The COD removal from raw POME to land application was about 86%, with 39% occurring in the composting platform and 47% in anaerobic ponds.

We compared the estimate GHG emissions from our composting trial case study, i.e. scenario 5, with 4 alternative scenarios that explore the effects of the proportion of aerobic/anaerobic decomposition and of the emission factors (Figure 2).

The first two scenarios compared potential complete anaerobic digestion of POME in ponds (scenario 1) with complete absorption of POME by the composting system (scenario 2). Scenario 3, 4 and 5 all used site-specific data for COD removal and diesel fuel consumption but used different emission factors, i.e., from the best- to the worst-case scenarios depending on varying combinations of default emission factors corrected by different pond depths.

Scenario 1 is the baseline with 100% anaerobic digestion of POME in deep ponds, following the IPPC guideline for waste water management [60]. Scenario 2 is a scenario with 100% of POME absorbed by the composting process and IPCC default emissions factors for compost [61]. Scenario 3 is our case study with a composting platform and anaerobic ponds, using low emissions for POME (correction factor of 0.2 for shallow ponds) [60] and negligible emissions from compost [35]. Scenario 4 is our case study and IPCC default values for $CH_4$ emissions from POME in deep pond (correction factor of 0.8 for deep ponds) [59] [60]. Scenario 5 is our case study with high $CH_4$ emissions from POME (100% of methane potential) [60] and the highest emission factors found in the literature for compost [11] [16] [22]. Diesel emissions are calculated using IPCC default values of 0.074 kg $CO_2$eq/MJ diesel [62], a density of 0.832 for diesel and a calorific value of 45.5 MJ/kg.

In ponds, GHG emissions are due to $CH_4$ only, whereas during the composting process emissions originate from several sources, in particular the biological processes can lead to both $CH_4$ and $N_2O$ emissions. This latter is a very potent GHG. In our case study, the added $CO_2$ emissions due to compost machinery had a negligible impact on the overall balance. Given the diversity of potential GHG emissions, the specificities of the composting infrastructure and processes can lead to varying combination of GHG emissions.

Composting can be a radical improvement compared to anaerobic digestion of POME in ponds, especially when all the POME is recycled through composting (Figure 2 Scenario 2), leading to a reduction of GHG emissions by 89%. The actual amount of GHG reduction depends on the efficiency of the composting process in terms of POME absorption and COD removal. In our case study (Figure 2 Scenario 5), where we combined both emissions from pond treatment and composting, the final global warming potential (or climate change impact indicator) from the waste management system would be similar to emissions usually attributed to 100% anaerobic treatment of POME in ponds (Figure 2 Scenario 1). Indeed, $N_2O$ emissions from composting compensated for $CH_4$ saving from pond treatment. Higher proportions of POME recycling in compost would be needed to lower more significantly the climate change impact.

Moreover, as emission factors influenced significantly the results (scenarios 3-5), considering site-specific emission factors would be needed in order to assess better the GHG reductions from composting.

### *4.3 Waste reduction and compost quality*

The total annual compost production was 31,482 t with an average moisture of 60%. This gives an average compost/EFB ratio of 51% and compost/FFB ratio of 11.2%. Compared to other studies reviewed (Table 3) nutrient content of the compost was average for P, quite high for K and rather low for N (Figure 3). The K content was quite variable over time and the lowest K content occurred at the period of the year where rainfall was the highest, suggesting losses from leaching.

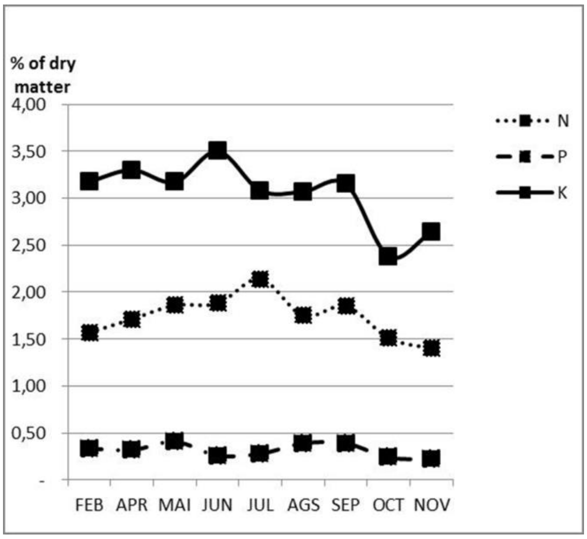


**Figure 3.** Nutrient content of industrial compost

### *4.4 Substitution of mineral fertilizers*

In the studied plantation, the crop needs in essential nutrients were met by application of imported mineral fertilizers and recycled organic by-products from the mill. The crop needs for each element are determined each year for each block (15 to 50 ha) through the use of leaf analysis [63]. Each block therefore receives a specific dose of each fertilizer, split in two applications. Compost is applied at a rate of two times 65 kg per palm and per year, equivalent to 17.5 t/ha/year. Compost is sometimes is often complemented with mineral fertilizers for K, P and Br.

In 2017, the fully mineral fertilization covered 86% of the area while compost was applied on 13% of the land, in some parts together with mineral fertilizers. Land application of POME in flat bed represented 1% of the land. In terms of total applied nutrients, compost covered 10% of all fertilizer use in the plantation (Table 9).

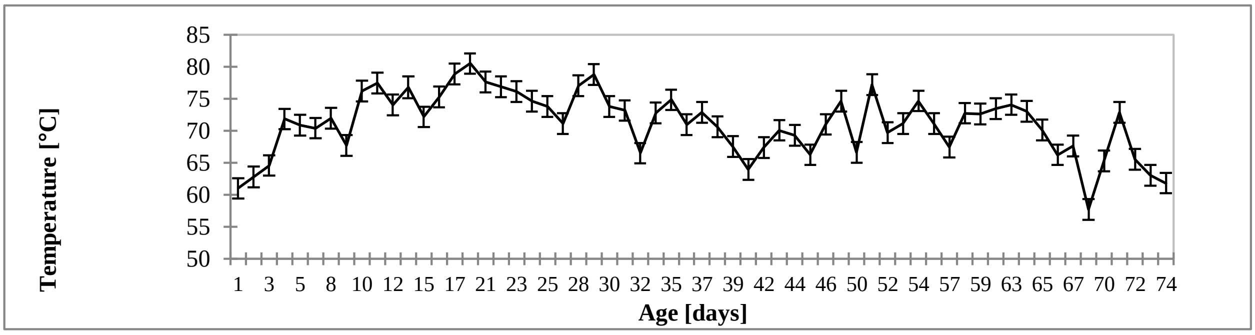


**Figure 4.** Temperature general trend

**Table 9.** Average doses of fertilizers applied. Mineral complement for K and P are often used with compost

| Average dose [kg/ha/year] | Mineral and compost | Mineral | Land application of effluent |
|---|---|---|---|
| Urea | 12 | 234 | - |
| DAP | 0 | 200 | - |
| Rock Phosphate | 11 | 31 | - |
| Triple Super Phosphate | **189** | 100 | - |
| KCl | **122** | 471 | - |
| Dolomite | 0 | 29 | - |
| Kieserite | 11 | 145 | - |
| Borax | 7 | 7 | - |
| Compost | 17,595 | - | - |
| Effluent [$m^3$] | - | 0 | 375 |

### *4.5 Composting trials*

*General kinetics of the composting process*

The composting process was purely thermophilic (Figure 4), with a regular increase in moisture and a temperature above 65°C. The degradation of organic matter was the highest during the first 10 days. The thermophilic phase was sustained by the frequent spraying of hot and highly fermentable POME and by the frequent turning. The compost never reached a mesophilic or maturation phase, and moisture was above 70% at the end of the process (Figure 5). The biological degradation of organic matter resulted in the loss of dry weight of 50% and 56% after 50 and 72 days respectively (Figure 6). This weight reduction led to an increase in nutrient content as shown in Table 10. With the increase of moisture during the process, the fresh weight reduction was only 26% and 34% of the original EFB weight, after 50 and 72 days respectively. Higher fresh weight and higher moisture compared to industrial data can be explained by the fact that the industrial compost usually undergoes a "curing and drying" period of 2-3 weeks before being weighed and applied in the plantation. Compared to the literature (Table 3) the end product had a high content in K, a low content in N and an average content in P (Table 10). Higher K content can be explained by a high K content of the original feedstock compared to the literature (Tables 1, 2, 4 and 10).

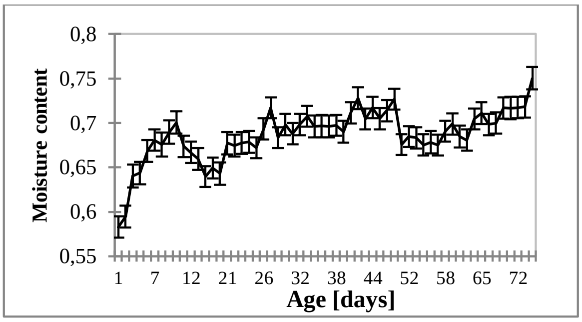


**Figure 5.** Moisture general trend

**Table 10.** Nutrient content at different composting stages (average of 3 protocols)

| Nutrient | N% | P% | K% | Mg% |
|---|---|---|---|---|
| EFB (day 0) | 1.05 | 0.21 | 3.20 | 0.30 |
| Compost (day 50) | 1.72 | 0.34 | 3.30 | 0.54 |
| Compost (day 72) | 1.91 | 0.43 | 3.20 | 0.72 |

The nutrient recovery efficiency varied between 30% for K to 70% for P (Figure 7). This can be explained by the combination of a high POME/EFB ratio and exposition to rainfall that washed away more than 50% of the total nutrients originally present in EFB and POME.

*Effect of treatments*

The parameters tested had a significant effect on the dry weight reduction and the nutrient recovery efficiency. The protocol B with the highest spraying frequency and POME/EFB ratio had the slowest kinetics of weight reduction and the lowest weight reduction at day 50 (Figure 6). Addition of urea in the compost (protocol B) did not accelerate composting and was associated with higher N losses (Figure 7). The protocol A with no additional urea and a lower dose of POME per application had better nutrient recovery rates than protocols B and C (Figure 7). No effect of the cover on the nutrient recovery rate or weight reduction was observed. The cover limited the increase of moisture during heavy rainfall but did not have a significant effect on the finale moisture and nutrient content of the compost, which was linked to the intensity of POME spraying.

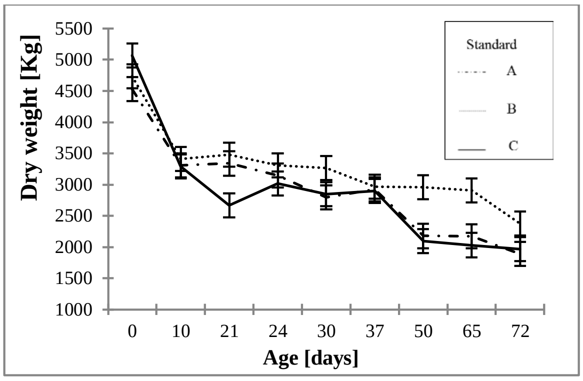


**Figure 6.** Dry weight evolution per protocol

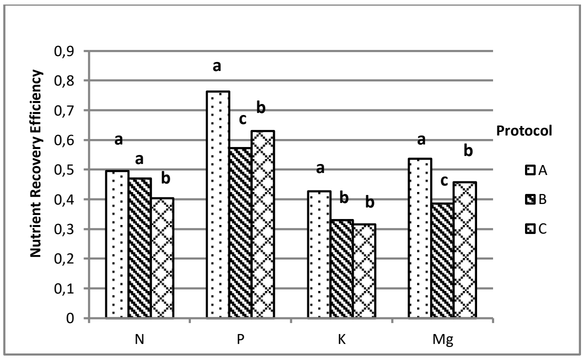


**Figure 7.** Nutrient Recovery Effciency per protocol. Different letters indicate significantly different values between protocols (Tuckey test, $p<0.05$)

## 5 DISCUSSION

*Fuel consumption*

Diesel consumption for composting will affect the net energy ratio of compost, as it is the main external source of energy for CPO production. We observed a fuel consumption of 3.3 L/ton of compost, which is in the low average of what can be found in the literature with values of 2.7 L [33], 6 L [64] or 7 L [35]. Diesel consumption in our case was just for turning the heap every 2 days, with no active aeration or compost screening. The fuel consumption could easily be reduced by adopting a turning interval of 3/10 days during the early thermophilic stage and a turning interval of 15/20 days in the mesophilic stage [65].

*POME leaching and COD removal*

Current LCI studies assume that the composting platform can absorb 100% of the POME from the mill, with a POME/EFB ratio of 3 $m^3$/t [32] [33] [34] [35]. This enables the removal of COD in fully aerobic conditions, drastically reducing methane emissions. Most of the reviewed studies on the composting process used a POME/EFB ratio ranging from 1 to 3 for spraying but none of them measured the importance of leachates. In our case study, a large proportion of the POME sprayed on compost was leached and recirculated to anaerobic ponds and only 39% of the COD could be considered as removed in aerobic conditions. More recently, a study [65] suggested that a roofed windrow composting system would completely absorb 0.7-1.5 $m^3$ POME/t EFB in 50 days, with full recycling of the compost leachates. Another study [66] showed absorption of 3 $m^3$ POME/t EFB in a roofed system with recycled leachates. Our study confirms that an open windrow composting system with a process of 50-70 days cannot absorb all effluents from the mill unless the platform is isolated from rain and leachates are recycled. However it could be the case if the POME/FFB ratio was decreased from 0.6 $m^3$/t to 0.25 $m^3$/t by using continuous sterilization and zero dilution water technology for oil recovery [53].

*Assumptions and default values for GHG emissions*

The first key parameter for calculating emissions is the initial COD content of POME and the final COD content of effluent, used for calculating potential methane emission. We found values of 87,000 mg/L in raw effluents and roughly 6,000 mg/L in final effluents, against a default value of 50,000 mg/L for COD removal in the literature [33] [34] [35].

The second parameter is the percentage of COD that can actually be absorbed and removed in aerobic conditions by the composting process, 39% here against 100% in most modeling assumptions.

Third, the emission factor used for estimating $CH_4$ emissions from COD removal during anaerobic treatment of POME. Stichnothe [32] used a factor of 0.251 kg $CH_4$/kg COD, which is the maximum emission for waste water [60]. The correction factor of 0.8 [59] for deep ponds (0.20 kg $CH_4$/kg COD) was used in more recent studies [33] [34]. Choo used an emission factor of 11.9 kg $CH_4/m^3$ POME [67], or an emission factor of 0.23 kg $CH_4$/kg COD if we consider the COD removal to be 50,000 mg/L during the anaerobic treatment. The lower estimate possible would be to use the IPPC correction factor of 0.2 [59] [60] for shallow ponds (0.05 kg $CH_4$/kg COD), which are sometimes found in agro-industries. RSPO GHG calculator is based on the value of 0.109 kg $CH_4$/kg COD measured by Yacob [68], which is intermediate between deep and shallow ponds found in the IPCC guidelines.

Fourth, GHG emissions from diesel fuel consumption in the composting platform can be accounted for [35] or neglected [34]. We showed in

Figure 2 that the global warming potential (or climate change impact) calculated for the composting platform is not much sensitive to diesel consumption.

Finally, one key parameter for GHG calculation is to know how to account for potential $N_2O$ and $CH_4$ emissions from the compost pile. Some published LCI consider that a properly managed compost emits negligible amounts of $N_2O$ and $CH_4$ [35], but IPCC standards suggest to use emissions factors or 0.5% of N for $N_2O$ and 1% of C for $CH_4$ [61], or defaults values of 4 kg $CH_4$/t of wet waste and 0.3 kg $N_2O$/t of wet waste if C and N content are not known. However emissions from compost found in the literature can be as high as 8.92 kg/t of wet waste for $CH_4$ and 1.36 kg/t of wet waste for $N_2O$ [22] or 7.5% of total organic C emitted as $CH_4$ and 7.3% of total nitrogen emitted as $N_2O$ [16]. $CH_4$ and $N_2O$ emissions in compost are very variable and depend on moisture, compaction and C/N ratio of the original feedstock. High moisture and compaction in the compost can reduce free air space and cause $CH_4$ emissions, while high aeration could favor $N_2O$ emissions [11] [16] [17]. We showed in Figure 2 that the GHG balance was very sensitive to anaerobic COD removal and $CH_4$ emissions from the compost piles. The latter is a risk that cannot be neglected with a high POME/EFB spraying protocol and high moisture in the compost pile (Figure 6). In our case study we found emissions of 755 $CO_2$eq/t CPO from the waste management system (figure 2- Scenario 4) in the average scenario, where other studies found ranges from 20 to 180 $CO_2$eq/t CPO for the composting sub-system [32] [33] [34] [35].

*Nutrient recycling, compost quality and compost use*

The average N-P-K content of the compost from our the trial were similar to the industrial compost of 2017 (Figure 2 and Table 10), but much lower than the ones used in other compost LCI [32] [33] [36]. This difference can be explained by the fact that they do not use specific values from composting trials but assume a NRE of 100% for all nutrients contained in POME and EFB. In an open window system without recycling the leachates, losses of nutrient were important, especially for K [46]. The hypothesis of high nutrient losses through leaching is supported by the fact that compost leachates had a slightly higher concentration in N, P and K than the raw POME (Tables 5 and 6). A high POME/EFB ratio will cause more losses if the leachates are not recycled (Figure 7). Another study showed that NRE close to 100% can be achieved for P, K and Mg if all leachates are recycled and recirculated on the compost in a closed system [65], but insisted on 30 to 35% losses of N due to gaseous emissions.

Losses of nitrogen due to ammonia volatilization are very common for compost in a range of 1% to 30% [11] [16] [69] and should be estimated in LCI. Additional urea used for composting could also be accounted for and might cause higher losses (Figure 7). The spraying interval can also affect the nutrient recovery (Figure 7) but its effect remains marginal compared to the roofing of the platform and the recycling of the leachates. Duration of the composting process over 50 days is also considered as a marginal considering the kinetics shown in Figure 7.

Other studies also used an average compost moisture of 50% [32] [63] [69] where we found a final moisture of 70-75%. Final moisture can vary according to the roofing of the platform, POME/EFB ratio, rainfall and drying period. Extra moisture would significantly impact the net weight of compost to be transported to the field. A drying period of 20 days (covered compost, no spraying) would help decrease the moisture to from 70-75% to 60-65% [65]. With a higher moisture and lower nutrient content, higher doses have to be applied in the field to cover the crop needs. The general assumption is that compost can completely replace mineral fertilizers at a dose of 10 t/ha/year [54] and therefore cover about 25% of the plantation needs in nutrients [36]. We found a compost use of 17.5 t/ha/year with mineral complementation when compost is applied, and an overall substitution ratio of 10%.

*Critical points for future LCA*

Previous LCI and LCA studies on palm oil mill co-composting have used default values and optimistic modeling assumptions to highlight the potential of compost for emission mitigation. Those studies are best-case scenarios, used to assess the potential of more sustainable waste management systems. They were useful to promote better practices among industries. Our study showed that actual savings and avoided emissions can vary greatly according to the type of composting system. Those variations should be taken into account into LCI, especially if LCA results are used for decision-making or certification standard such as the roundtable on sustainable palm oil (RSPO) or the United Nations' Clean Development Mechanisms. By comparing general assumptions and default values with more site specific-data and extreme values, the LCA approach can help bridging implementation gaps and identify environmental hotspots. We therefore propose 4 critical parameters to evaluate the real impact of composting on the mitigation pathways cited above: i) the proportion of COD reduction occurring in anaerobic conditions during effluent treatment ii) the nutrient recovery efficiency for each nutrient iii) the final moisture of the compost iv) the net fresh weight reduction or compost/EFB ratio. Those quantifiable indicators should be measured on site to improve composting systems. Different composting systems and their emission values could be modeled to account for variability in composting systems. In this perspective we identified 7 critical practices that should be used for scenario and sensitivity analysis. Those practices are i) the POME/FFB ratio from the mill ii) the pretreatment of POME iii) the POME/EFB ratio for composting iv) the roofing of the composting platform v) the turning frequency vi) the recycling of leachates and vii) the process duration and drying period.

*Methodological limits*

The main limit of our study is the uncertainty regarding the COD reduction and nitrogen losses from POME along the effluent treatment system. We could estimate the COD removal on the composting platform by calculating an in-and-out COD balance, but we lacked information on $CH_4$ emissions that could occur from anaerobic conditions on the composting platform. Emission factors used for direct $N_2O$ losses were very uncertain and more knowledge on site-specific emissions would be needed taking into account critical parameters such as compost moisture and aeration. Finally, we did not quantified $NH_3$ emissions and subsequent indirect $N_2O$ emissions. The effect of compost application on field emissions, soil health and soil organic carbon stocks also remain a critical parameter that would have to be included in future LCI [71] [72].

## 6 CONCLUSION

Through the literature review and the composting trial, this study highlighted methodological adjustments necessary to account for the variability of the composting process in LCA. Both quantity and quality of palm oil residues compost are influenced by inter-connected technological choices along the whole process. The sterilization and oil recovery technology used in the mill determine the total amount of liquid effluent to be treated. Energy consumption of the composting process depends on the composting technology and the turning frequency. The COD content of effluents will determine methane emission potential. GHG emissions and the final climate change impact are very sensitive to the emission factors for both ponds and compost piles, while site-specific factors are merely available. The roofing of the composting platform is a critical parameter that will affect nutrient losses and the amount of effluent that can be absorbed by the composting platform, and therefore methane emissions. POME/EFB ratio as well as the spraying frequency will affect the nutrient recovery rate. The final nutrient content will determine the dose of compost to be applied in the field and the area covered by compost. Moreover, the final weight reduction of waste will impact the fuel consumption and cost for compost application. The optimization of final agronomical and environmental impacts of compost hence depends on a fine understanding of all process steps and trade-offs. Such a deep understanding should help to improve current LCI for palm oil production and provide guidelines for palm oil mill residues composting.

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## REFERENCES

[1] USDA, 2006. Chapter III- Statistics of oilseeds, fats and oils. 30p. https://www.nass.usda.gov/Publications/Ag_Statistics/2006/CHAP03.PDF

[2] Khatun, R., Reza, M.I.H., Moniruzzaman, M., Yaakob, Z., 2017. Sustainable oil palm industry: The possibilities. Renewable and Sustainable Energy Reviews 76, 608-619.

[3] Afriyanti, D., Kroeze, C., Saad, A., 2016. Indonesia palm oil production without deforestation and peat conversion by 2050. Science of the total environment 557-558, 562-570.

[4] Dislich, C., Keyel, A.C., Salecker, J., Kisel, Y., Meyer, K.M., 2016. A review of the ecosystem functions in oil palm plantations, using forests as a reference system: Ecosystem functions of oil palm. Biological Reviews (2016) 000-000.

[5] Bessou, C., Verwilghen, A., Beaudoin-Ollivier, L., Marichal, R., Ollivier, J., Baron, V., Bonneau, X., *et al*, 2017. Agroecological

practices in oil palm plantations: examples from the field. OCL 24 (3), D305.

[6] Bare, J.C., Hofstetter, P., Pennington D.W., de Haes, H.A.U., 2000. Midpoints versus endpoints: The sacrifices and benefits. Int. J. Life Cycle Assess. 5(6), 319-26.

[7] Baharuddin, A.S., Kazunori, N., Abd-Aziz S., Tabatabaei, M., Abdul Rahman, N.A., Hassan, M.A., *et al*, 2009. Characteristics and microbial succession in co-composting of oil palm empty fruit bunch and partially treated palm oil mill effluent. Open Biotechnol J. 3, 92–100.

[8] Partanen, P., Hultman, J., Paulin, L., Auvinen, P., Romantschuk, M., 2010. Bacterial diversity at different stages of the composting process. BMC Microbiol 10(1), 94.

[9] Yu, H., Zeng, G., Huang, H., Xi, X., Wang R., Huang, D., *et al*, 2007. Microbial community succession and lignocellulose degradation during agricultural waste composting. Biodegradation 18 (6):793-802.

[10] Francou, C., Poitrenaud, M., Houot, S., 2005. Stabilization of organic matter during composting : Influence of process and feedstocks. Compost Science and Utilization 13(1), 72-83.

[11] Abd El Kader, N., Robin, P., Paillat, J.M., Leterme, P., 2007. Turning, compacting and the addition of water as factors affecting gaseous emissions in farm manure composting. Bioresour. Technol. 98(14), 2619-28.

[12] Oudart, D., 2013. Modélisation de la stabilisation de la matière organique et des émissions gazeuses au cours du compostage d'effluents d'élevage. Toulouse, INSA. Available on:http://www.theses.fr/ 2013ISAT0044

[13] Ceglie, F.G., Adbelrahman, H.M., 2014. Ecological intensification through nutrients recycling and composting in organic farming. In: Composting for sustainable agriculture. Springer. Editor: Maheshwari, D.K. 2-22.

[14] Bernal, M.P., Paredes, C., Sanchez Monedero, M.A., Cegarra, J., 1998. Maturity and stability parameters of composts prepared with a wide range of organic wastes. Bioresour. Technol. 63, 91-9.

[15] Pansu, M., Thuriès, L., 2003. Kinetic of C and N mineralization, N immobilization and N volatilization of organic inputs in soil. Soil Biol. Biochem. 35, 37-48.

[16] Jiang, T., Schuchardt, F., Li, G., Guo, R., Zhao, Y., 2011. Effect of C/N ratio, aeratio rate and moisture content on ammonia and greenhouse gas emission during the composting. J. Environ. Sci. 23(10), 1754-1760.

[17] Yuan, J., Chadwick, D., Zhang, D., Li, G., Chen, S., Luo, W., et al, 2016. Effects of aeratio rate on maturity and gaseous emissions during sewage sludge composting. Waste Management 56, 403-10.

[18] Bernal, M.P., Sanchez-Monedero, M.A., C. Paredes, C., Roig, A., 1998. Carbon mineralization from organic wastes at different composting stages during their incubation with soil. Agriculture, Ecosystems and Environment. 69, 175-189.

[19] Recycled Organics Unit, 200. Life Cycle Inventory and Life Cycle Assessment for Windrow Composting System. The University of New South Wales. Second Edition. 171p.

[20] Saer, A., Lansing, S., Davitt, N.H., Graves, R.E., 2013. Life cycle assessment of a food waste composting system: environmental impact hotspots. J. Clean. Prod. 52, 234-44.

[21] Edwards, J., Othman, M., Crossin, E., Burn, S., 2017. Life cycle inventory and mass-balance of municipal food waste management systems: Decision support methods beyond the waste hierarchy. Waste Manag. 69, 577-91.

[22] Sánchez, A., Artola, A., Font, X., Gea, T., Barrena, R., Gabriel, D., *et al*, 2015. Greenhouse Gas from Organic Waste Composting: Emissions and Measurement. Environmental Chemistry Letters 13(3), 223-238.

[23] Boldrin, A., Andersen, J.K., Møller, J., Christensen, T.H., Favoino, E., 2009. Composting and compost utilization: accounting of greenhouse gases and global warming contributions. Waste Manag. Res. 27(8), 800-12.

[24] Bessou, C., Chase, L.D.C., Henson, I.E., Abdul-Manan, A.F.N., Milà i Canals, L., Agus, F., *et al*, 2014. Pilot application of PalmGHG, the RoundTable on Sustainable Palm Oil greenhouse

gas calculator for oil palm products. J. Clean. Prod. 73, 136-45.

[25] Reijnders, L., Huijbregts, M.A.J., 2008. Palm oil and the emission of carbon-based greenhouse gases. J. Clean. Prod. 16(4), 477-82.

[26] Subramaniam, V., May, C.Y., Muhammad H., Hashim, Z., Tan, Y.A., Wei, P.C., 2010. Life cycle assessment of the production of crude palm oil. J. Oil. Palm. Res. 22, 895-903.

[27] Wicke, B., Dornburg, V., Junginger, M., Faaij, A., 2008. Different palm oil production systems for energy purposes and their greenhouse gas implications. Biomass Bioenergy 32(12), 1322-1337.

[28] Pardon, L., Bessou, C., Nelson, P.N., Dubos , B., Ollivier, J., Marichal, R., *et al*, 2016. Key unknowns in nitrogen budget for oil palm plantations, A review. Agron. Sustain. Dev. 36: 20.

[29] Dubos, B., Snoeck, D., Flori, A., 2016. Excessive use of fertilizer can increase leaching processes and modify soil reserves in two ecuadorian oil palm plantations. Expl. Agr. 14p.

[30] Madaki, Y.S., Seng, L., 2013. Pollution Control: How Feasible is Zero Discharge Concepts in Malaysia Palm Oil Mills. Am. J. Eng. Res. 2, 239-252.

[31] Wood, B.J., Pillai, K.R., Rajaratnam, J.A., 1979. Palm oil mill effluent disposal on land. Agric. Wastes 1(2), 103–127.

[32] Stichnothe, H., Schuchardt, F., 2010. Comparison of different treatment options for palm oil production waste on a life cycle basis. Int. J. Life Cycle Assess. 15(9), 907-915.

[33] Nasution, M.A., Wibawa, D.S., Ahamed, T., Noguchi, R., 2018. Comparative environmental impact evaluation of palm oil mill effluent treatment using a life cycle assessment approach: A case study based on composting and a combination for biogas technologies in North Sumatera of Indonesia. J. Clean Prod. 184, 1028-1040.

[34] Stichnothe, H., Schuchardt, F., 2011. Life cycle assessment of two palm oil production systems. Biomass Bioenergy 35(9), 3976-84.

[35] Norhasmillah, A.H., Puah C.W., Ibrahim N.A., Baharuddin, A.S., Choo, Y.M., 2013. Life cycle inventory of the commercial production of compost from oil palm biomass: a case study. Environ Dev. Sustain. 15(6), 1663-70.

[36] Yoshizaki, T., Shirai, Y., Hassan, M.A., Baharuddin, A.S., Raja Abdullah, N.M., Sulaiman, A., *et al*, 2013. Improved economic viability of integrated biogas energy and compost production for sustainable palm oil mill management. J. Clean. Prod. 44, 1-7.

[37] Singh, R.P., Ibrahim, M., Esa, N., Iliyana, M.S., 2010. Composting of waste from palm oil mill: a sustainable waste management practice. Rev Environ Sci 9, 331-344.

[38] Singh, R.P., Embrandiri, A., Ibrahim, M.H., Esa, N., 2011. Management of biomass residues generated from palm oil mill: Vermicomposting a sustainable option. Resour Conserv Recycl 55(4), 423-34.

[39] Abu Zahrim, Y., Asis, T., 2010. Production of non-shredded empty fruit bunch semi-compost. The Institution of Engineers Malaysia, 71 (4), 11-17.

[40] Ahmad, M.N., Mokhtar, M.N., Baharuddin A.S., Hock, L.S., Ahmad Ali, S.R., Abd-Aziz S., et al, 2011. Changes in physicochemical and microbial community during co-composting of oil palm frond with palm oil mill effluent anaerobic sludge. BioResources, 6 (4), 4762-4780.

[41] Baharuddin, A.S., Hock, L.S., Yusof, M.Z., Rahman, N.A.A., Shah, U.K., Hassan, M.A., et al, 2010. Effects of palm oil mill effluent (POME) anaerobic sludge from 500 m 3 of closed anaerobic methane digested tank on pressed-shredded empty fruit bunch (EFB) composting process. Afr. J. Biotechnol 9 (16), 2427–2436.

[42] Baharuddin, A.S., Wakisaka, M., Shirai, Y., Abd-Aziz, S., Abdul Rahman, N.A., Hassan, M.A., 2009. Co-Composting of Empty Fruit Bunches and Partially treated Palm Oil Mill Effluent in Pilot Scale. Int. J. Agric. Res. 4(2), 69-78.

[43] Mohammad, N., Alam, M.Z., Kabashi, N.A., 2013. Development of composting process of oil palm industrial wastes by multi-enzymatic fungal system. J Mater Cycles Waste Manag 15(3), 348-356.

[44] Goenadi, D.H., Away, Y., Sukin, Y., Yusuf, H.H., Gunawan, Aritonang, P., 1998. Pilot-Scale composting of empty fruit bunches of oil palm using lignocellulosic composting. In Bali: IOPRI; 1998.

[45] Hock, L.S., 2009. Physicochemical changes in windrow co-composting process of oil palm mesocarp fiber and palm oil mill effluent anaerobic. Austalian J Basic Appl Sci. 3(3), 2809-2816.

[46] Salètes, S., Siregar, F.A., Caliman, J.P., Liwang, T., 2004. Ligno-cellulose composting: Case study on monitoring oil palm residuals. Compost Sci. Util. 12(4), 372-382.

[47] Suhaimi, M., Ong., H.K., 2001. Composting Empty Fruit Bunches of Oil Palm. Malaysian Agricultural Research and Development Institute (MARDI). http://www.agnet.org/library.php?func=view&id=20110804151206

[48] Schuchardt, F., Balcke, S., Becker, F., Guritno, P., Herawan, T., Darnoko, D., et al., 2000. Production of compost from EFB. In: Proceedings of the 2000-II IOPRI Oil Palm Technical Meeting, Medan. Indonesian Oil Palm Research Institute.

[49] Schuchardt, F., Darnoko, D., Guritno, P., 2002. Composting of empty oil palm fruit bunch (EFB) with simultaneous evaporatio of oil mill waste water (POME). In: Proceedings of International Oil Palm Conference, Bali, Nusa Dua; 2002.

[50] Thambirajah, J.J., Zulkali, M.D., Hashim M.A., 1995. Microbiological and biochemical changes during the composting of oil palm empty-fruit-bunches: Effect of nitrogen supplementation on the substrate. Bioresour Technol 52, 133-44.

[51] Yahya, A., Sye, C.P., Ishola, T.A., Suryanto, H., 2010. Effect of adding palm oil mill decanter cake slurry with regular turning operatio on the composting process and quality of compost from oil palm empty fruit bunches. Bioresour Technol 101 (22), 8736-8741.

[52] Saelor, S., Kongjan, P., O-Thong, S., 2017. Biogas Production from Anaerobic Co-digestion of Palm Oil Mill Effluent and Empty Fruit Bunches. Energy Procedia 138, 717-722.

[53] Schuchardt, F., Wulfert, K., Herawan, T., 2008. Effect of new palm oil mill processes on the EFB and POME utilization. J. Oil Palm Res. Special Issue 2008, 21-31.

[54] Tohiruddin, L., Foster, H.L., 2013. Superior effect of compost derived from palm oil mill by-products as a replacement for inorganic fertilizers applied to oil palm. J Oil. Palm Res. 25(1), 123–137.

[55] Darmosarkoro, W., Sutarta, E.S., 2002. Application of EFB compost on acidic soil in North Sumatra to increase soil bases and decrease aluminum. In: Enhancing oil palm industry development through environmentally friendly technology, Bali, Indonesia.

[56] Supriatna, J., Baron, V., Sadasiban, R., Bonneau, X., 2018. Composting For Sustainable Palm Oil Production, In Int Conf Oil Palm Env (ICOPE), Nusa Dua, Indonesia.

[57] Carron, M.P., Pierrat, M., Snoeck, D., Villenave, C., Ribeyre, F., Suhardi, *et al*, 2015. Temporal variability in soil quality after organic residue application in mature oil palm plantations. Soil Res. 53, 205-215.

[58] Tao, H.H., Slade, E.M., Willis, K.J., Caliman, J.P, Snaddon, J.L., 2016. Effects of soil management practices on soil fauna feeding activity in an Indonesian oil palm plantation. Agric. Ecosyst. Environ. 218, 133-40.

[59] United Nation. 2019. AMS-III.H: - Methane Recovery in wastewater treatment. Version 19.0. United Nations Framework Convention on Climate Change.40p. https://cdm.unfccc.int/methodologies/DB/K7FDTJ4FL3432I1UKRNKLDCUFAMBX7

[60] International Panel on Climate Change. 2019. Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 5: Waste Water Treatment and discharge. 68p. https://www.ipccnggip.iges.or.jp/public/2019rf/index.html

[61] International Panel on Climate Change. 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Volume 5 Chapter 4 : Biological treatment of solid waste. 8p.

[62] International Panel on Climate Change. 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Volume 2 Chapter 3 :Mobile Combustion. 78p.

[63] Caliman, J.P., Daniel, C., Tailliez, B., 1994. La nutrition minérale du palmier à huile. Plant. Rech. 1(3), 36-54.

[64] Yoshizaki, T., Shirai, Y., Hassan, M.A., Baharuddin, A.S., Abdullah, N.M.R., Sulaiman, A., *et al*, 2012. Economic analysis of biogas and compost projects in a palm oil mill with clean development mechanism in Malaysia. Environ. Dev. Sustain. 14(6), 1065-79.

[65] Baron, V., Supriatna, J., Maréchal, C., Sadasiban, R., Bonneau, X., 2019. Waste reduction and nutrient recovery during the co-composting of empty fruit bunches and palm oil mill effluent. Menera Perkebunan, In Press.

[66] Ling-Hoak, O., Keong-Hoe, L., Khoon-San, C., 2007. Conversión de efluentes y tusas en fertilizante orgánico con cero desperdicios. Palmas 28 (2), 180-190.

[67] Choo, Y.M., Muhamad, H., Hashim, Z., Subramaniam, V., Puah, C.W., Tan, Y., 2011. Determination of GHG contributions by subsystems in the oil palm supply chain using the LCA approach. Int. J. Life Cycle Assess. 16 (7), 669-81.

[68] Yacob, S., Hassan, M.A., Shirai, Y., Wakisaka, M., Subash, S., 2005. Baseline study of methane emission from open digesting tanks of palm oil mill effluent treatment. Chemosphere 59 (11), 1575-81.

[69] Shen, Y., Ren, L., Li, G., Chen, T., Guo, R., 2011. Influence of aeratio on $CH_4$, $N_2O$ and $NH_3$ emissions during aerobic composting of a chicken manure and high C/N waste mixture. Waste Manag. 31(1), 33-38.

[70] Chiew, Y.L., Shimada, S., 2013. Current state and environmental impact assessment for utilizing oil palm empty fruit bunches for fuel, fiber and fertilizer – A case study of Malaysia. Biomass Bioenergy 51, 109-124.

[71] Stichnothe, H., Bessou C., 2017. Challenges for Life Cycle Assessment of Palm Oil Production System. IJolCAS 1 (2), 1-9.

[72] Wiloso, E.I., Bessou, C., Heijungs, R., 2015. Methodological issues in comparative life cycle assessment: treatment options for empty fruit bunches in a palm oil system. Int. J. Life Cycle Assess 20(2), 204-16.