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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Abstrak

Pengelolaan produk sampingan pabrik kelapa sawit (tandan buah kosong - TBK dan limbah pabrik kelapa sawit - POME) merupakan sebuah isu yang menjadi perhatian di Indonesia. Co-composting merupakan proses pengelolaan limbah yang menjanjikan untuk mengurangi dampak lingkungan dan mengembalikan bahan organik ke tanah. Studi ini merupakan bagian dari proyek Life Cycle Assessment (LCA) yang bertujuan untuk menunjukkan dampak lingkungan terbesar dari suatu rantai produksi minyak sawit secara tepat. Kajian ini secara khusus melakukan inventarisasi data terhadap proses pengomposan pada lokasi data spesifik. Data terkait daur ulang biomassa, kebutuhan energi, dan karakteristik kompos yang dihasilkan dicatat pada industri kelapa sawit lebih dari satu tahun. Pada kondisi setempat, unsur hara terlarut yang tinggi dari kompos tercatat masih basah dan panas (fase termofilik). Proses pengomposan hanya menyebabkan 40% penghindaran metana dibandingkan dengan proses anaerob POME dan efisiensi pemulihan nutrisi secara umum masih di bawah 50%. Kami mengidentifikasi beberapa parameter kritis untuk meningkatkan kualitas lingkungan melalui proses pengomposan: i) rasio POME / TBS dari pabrik, ii) atap platform pengomposan, iii) rasio POME / EFB, iv) frekuensi pergantian, v) daur ulang lindi dan vi) durasi proses dan periode pengeringan. Pemulihan nutrisi dan dosis kompos yang diterapkan di lapangan tergantung pada semua parameter yang saling terhubung. Data yang disajikan akan digunakan dalam model LCA untuk menentukan manfaat lingkungan melalui berbagai sistem pengomposan seperti POME dan EFBenvironmental impact of palm oil production is a global concern that has been scrutinized by the scientific community.

Kata kunci: *Palm Oil; Life Cycle Inventory; Compost ; EFB ; POME*

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^{TM}) 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).

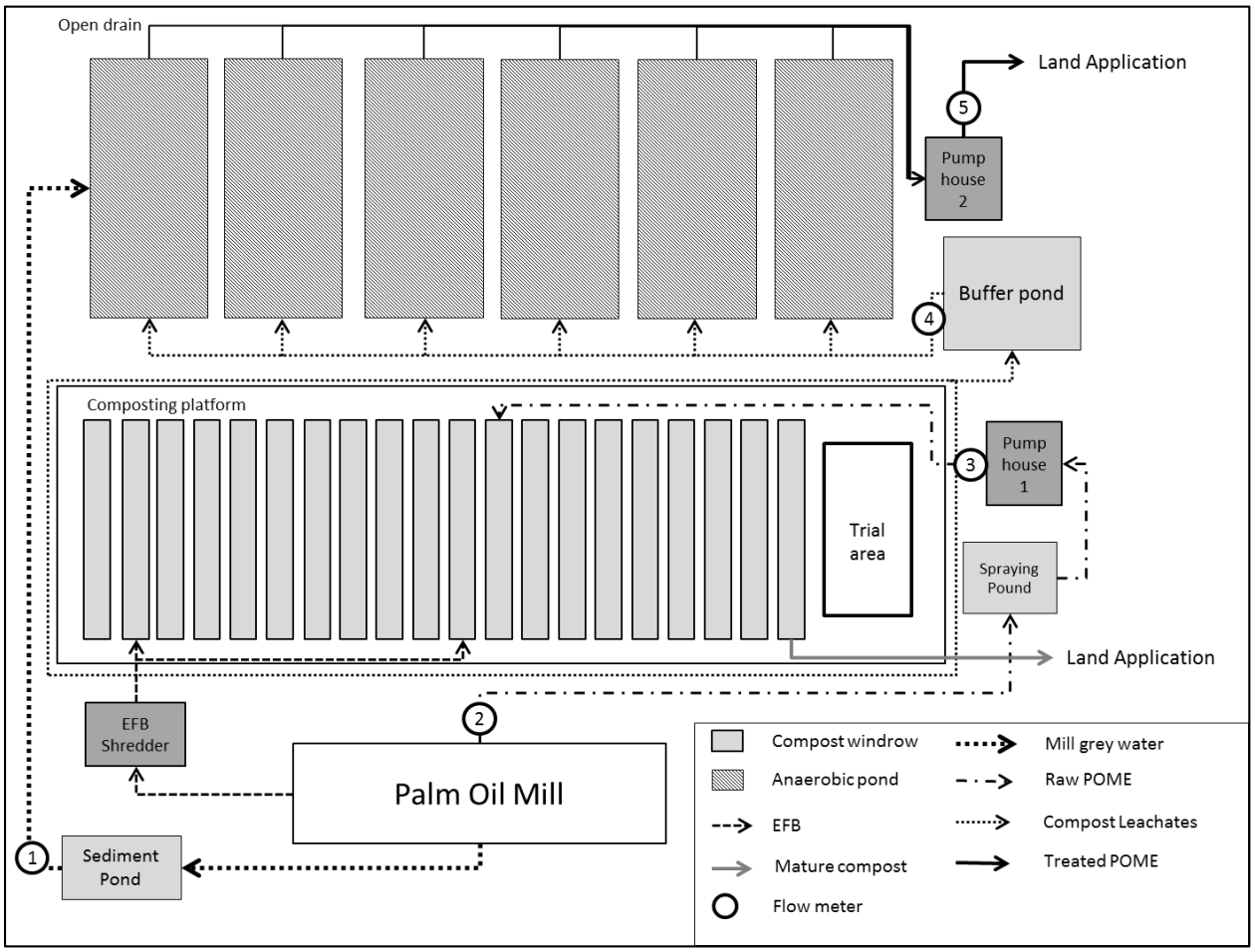

Figure 1. Waste management system in the mill. Numbers 1 to 5 indicate the location of flowmeter that were used to measure the flow of effluents at each treatment stage 1) Mill grey water 2) Hot raw POME 3) Cooled raw POME 4) Compost leachates 5) Treated effluent for land application

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^{TM} 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.

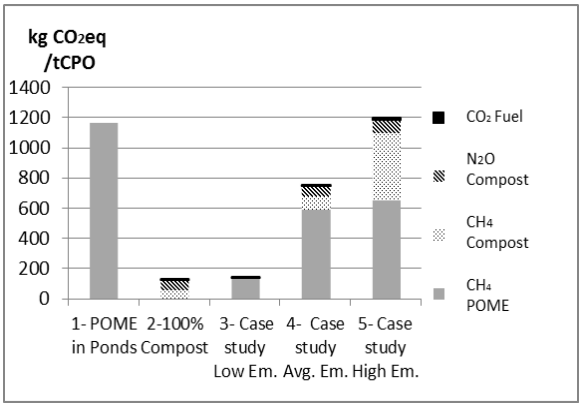

Figure 2. Different scenarios for GHG emissions from waste management in the mill

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_2eq/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.

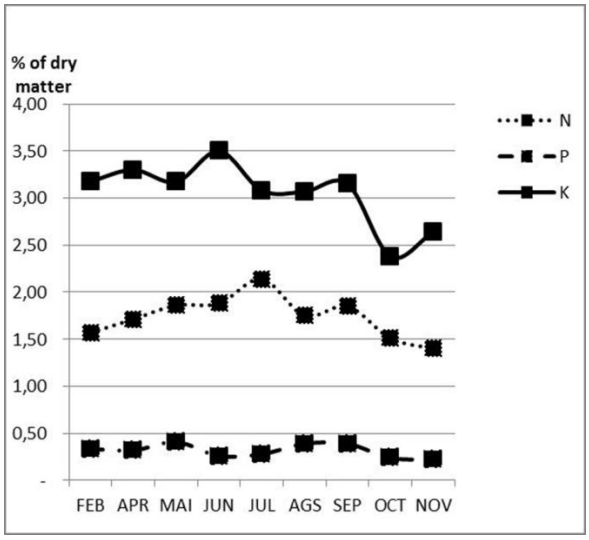

Figure 3. Nutrient content of industrial compost

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).

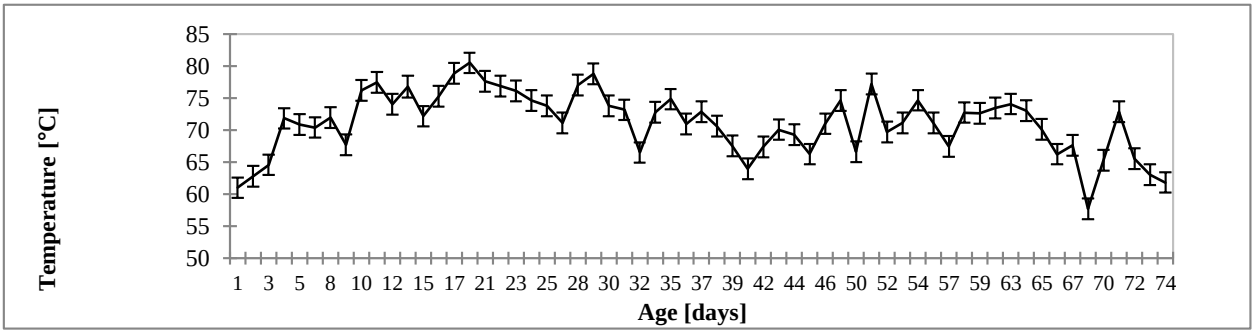

Figure 4. Temperature general trend

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).

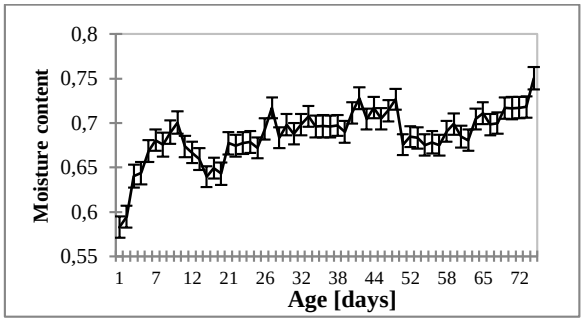

Figure 5. Moisture general trend

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.

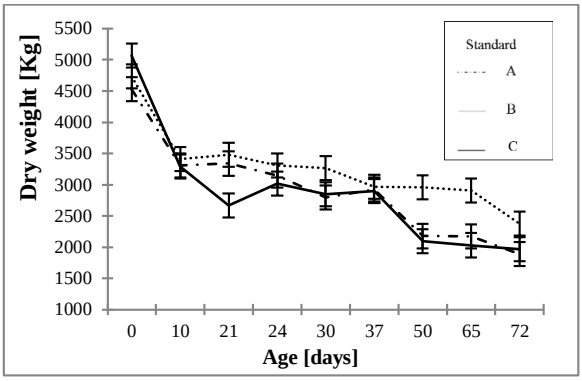

Figure 6. Dry weight evolution per protocol

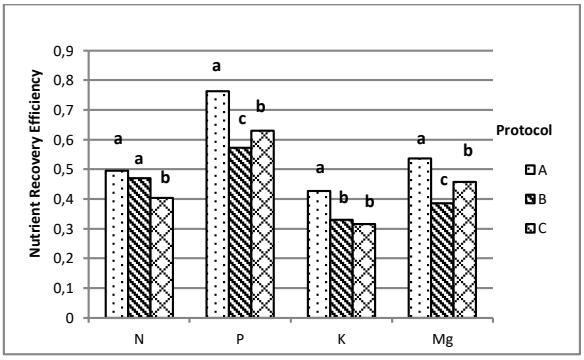

Figure 7. Nutrient Recovery Effciency per protocol. Different letters indicate significantly different values between protocols (Tuckey test, $p<0.05$)

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_2eq/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_2eq/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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