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Greenhouse Gas Assessment and Strategies to Achieve CO₂ Sequestration in the Brazilian Palm Oil Life Cycle

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Abstract

As the palm oil production is expanding in Brazilian Amazon region, this study aimed to determinate the greenhouse gas (GHG) emissions since the agricultural phase to transportation of crude palm oil (CPO) and then indicate strategies to achieve the CO₂ sequestration. The scope of this study comprised since the stage of oil palm seedlings production until the transportation of CPO. Inventory data for the year of 2009 included the agricultural production of fresh fruit bunches (FFB) and the extraction and transportation of CPO. The management of palm oil mill effluent (POME), use of fertilizers, fuels, pesticides, and electricity contributed to 66.5, 17.9, 15.1, 0.4, and 0.1% of the total emissions, respectively. Agricultural phase, CPO extraction, and transportation emitted 32,131, 79,590, and 1,104 t CO₂-eq, respectively. The carbon (C) footprint was 0.79 t CO₂-eq / t CPO, and the highest GHG emissions were associated to the management of POME. On the other hand, the use of all residues from the mill as fertilizer substitute can minimize the GHG emissions and increase soil C stocks. In addition, the methane (CH₄) from POME captured and used for steam or electricity is also a viable alternative to reduce the GHG emissions.

Keywords: carbon dioxide, crude palm oil, fresh fruit bunches, methane, nitrous oxide, palm oil mill effluent

1. Introduction

Oil palm (*Elaeis guineensis* Jacq.) is the most produced oil crop in the world due to its high productivity in relation to other oleaginous crops (e.g., soybean, sunflower, and rapeseed), and could meet growing global demand that is estimated to reach 240 million tons of palm oil by 2050 [1]. In Brazil, the cultivated area with oil palm is about 236,000 ha, including areas of agro-industries, small- and medium-sized farmers, family farmers and members of agrarian reform. It is estimated that

88% of Brazilian palm oil production was located at Pará State, while Bahia and Roraima States account for 11 and 1% of production, respectively [2].

There is a great potential for development of palm oil chain in Brazil. The Brazilian government envisions a 35% expansion of oil palm production in the Amazon region due to its favorable soil and climate conditions and large amount of available lands. The Program for Sustainable Production of Palm Oil in Brazil has been promoting oil palm plantations but limiting the expansion only to degraded lands [3]. There was an encouragement for the cultivation of oil palm in the northern region due to its high productivity and potential for inclusion in the biodiesel agenda. Pará State continued to be targeted as the largest potential producer, and there was an estimated expansion of 330,000 ha until 2020 [4].

The environmental impacts of palm oil production can be accessed from a life cycle point of view, where the greenhouse gas (GHG) emissions can be accounted since from oil palm cultivation, crude palm oil (CPO) extraction, CPO transportation, and recycling or disposal of residues from the mill [5, 6]. According to Menichetti and Otto [7], the impacts depend on the consumption of conventional fuels, fertilizers, and the wastes generated. We hypothesized that the main source of GHG emissions in the palm oil production is related to CPO extraction and disposal of liquid waste from the mill.

Therefore, the aim of this study was to access the GHG emissions derived from the agricultural production, CPO extraction and transportation in an agro-industry farm located at Pará State, Amazon region, Brazil. Additionally, we aim to propose strategies for reducing GHG emissions and for promoting the CO₂ sequestration.

2. Materials and methods

2.1 Location of the study area

The study was carried out in 2009 in a commercial farm located in the municipality of Tailândia (48°46'W, 2°27'S), Pará State, Brazil (**Figure 1**). The company had a total area of 107,000 ha, where 60% is occupied with native vegetation, 36% with oil palm plantation, and 4% with infrastructure. The native vegetation is tropical rainforest. According to Köppen classification, the climate is Afi (tropical monsoonal). The rainfall for 2009 was 2705 mm year⁻¹ and the mean temperature was 26.5°C. The temperature ranged from 22.6 to 33.4°C and the mean of annual relative humidity was higher throughout the year. The mean altitude of the region is 30 m, and the soil is well drained with medium clay content (18–29%), and classified as “Latossolo Amarelo distrófico típico” in the Brazilian System of Soil Classification [8] and as Oxisol (Xanthic Hapludox) in the USDA classification [9].

2.2 Palm oil system description

The palm oil supply chain consists of three subsystems (**Figure 2**): seedlings production, fresh fruit bunches (FFBs) production, and crude palm oil (CPO) extraction. Several processes are involved in the production of FFB, including planning, nursery establishment (seedlings cultivation), soil preparation, field establishment, field maintenance, harvesting and collection of FFB and replanting [10]. Considering all steps, the agricultural phase of oil palm production lasts for around 25–30 years [1].

The industrial phase consists of CPO extraction. The palm oil mill is located near to the oil palm plantations to facilitate the timely transportation and effective processing of FFB. Processing in the palm oil mill involves four major unit operations: sterilization, threshing and stripping of fruits, digestion, and oil extraction [11].

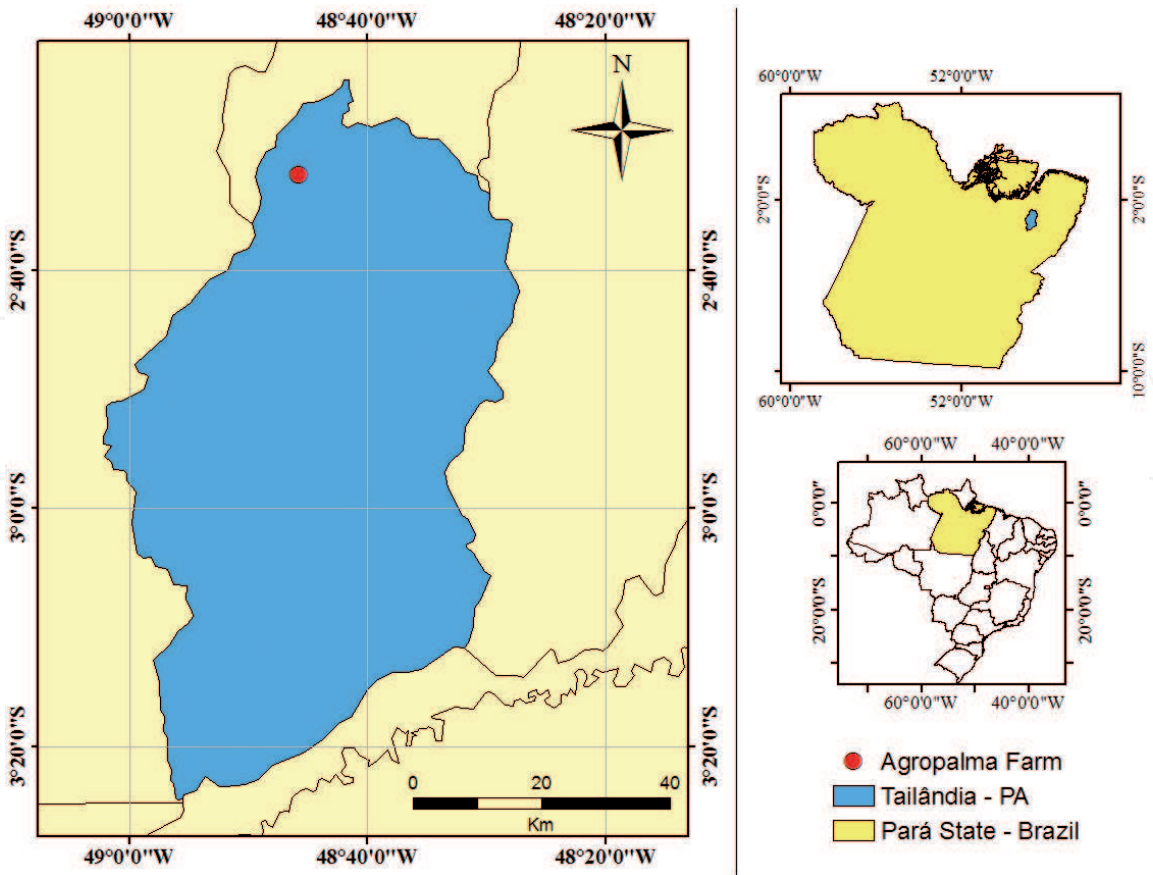


Figure 1.
Location map of the study area in the Brazilian Amazon region.

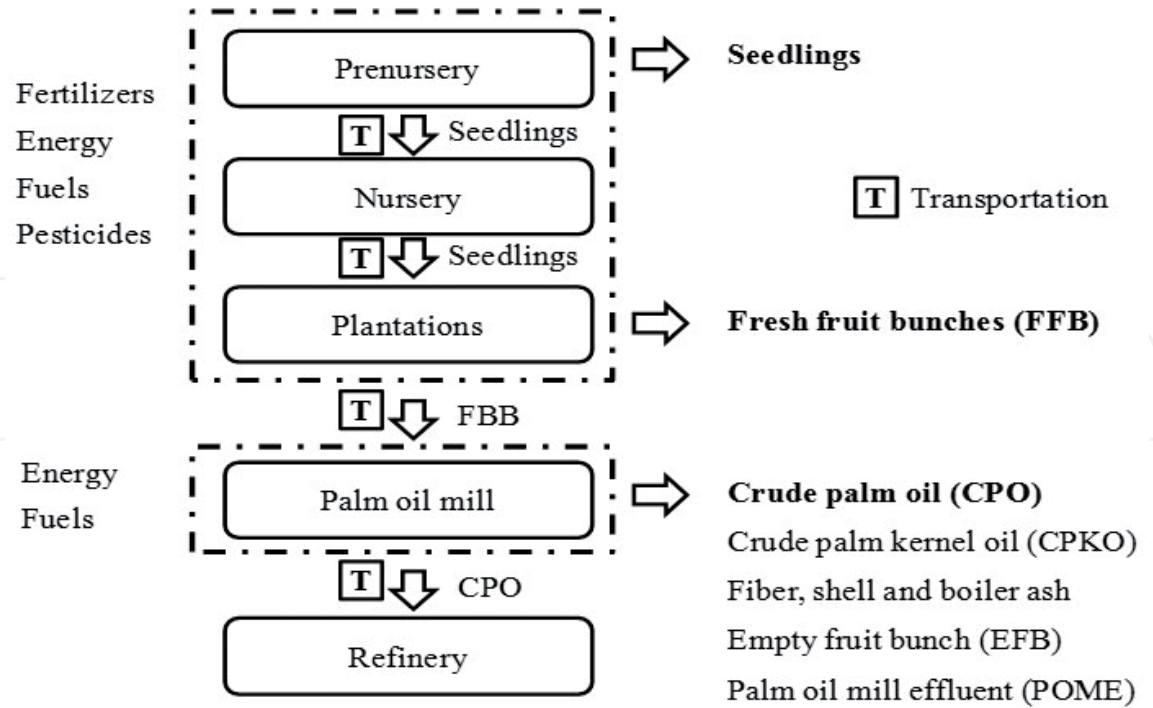


Figure 2.
Description of the CPO production system in the Brazilian Amazon region.

Subsequently, the CPO, the main product from the palm oil mill, is transported to a refinery aiming to produce refined palm oil (RPO). Although it is possible to use CPO as raw material, the biodiesel production is based on fatty acids extracted from palm oil fruit through the refining process [12].

2.2.1 Agricultural phase

In the oil palm cultivation, the first stage in the agricultural phase is the seedlings production. In prenursery, seeds are sown in small polyethylene bags (0.5 L) where the seedlings are kept under the shade to protect them from direct sunlight until they are 3 months old. In the subsequent main nursery stage, the seedlings are transferred to large polyethylene bags (18 L) and grown without a protective shade until they are 12 months old, when they are considered ready to be shifted to the plantations. Sprinkler systems are used to provide sufficient water in prenursery and nursery (8 mm day⁻¹). The seedlings are supplied with nutrients by fertilizer applications.

The palms from nursery are transferred to oil palm plantations and planted at a density of 143 plants/ha on a mineral soil with low and medium clay content. About some time after palm plantation, a legume used as cover crop (*Pueraria phaseoloides*) is sown. The cover crop prevents erosion and fixes nitrogen from the atmosphere in their root nodules, especially during the stage when the palms are young. A circle with no vegetation is established around each plant, preventing competition of weeds. The circle allows the herbicide application and the easy access for harvesting and picking of loose fruits.

The fertilizers applied in the oil palm plantations are potassium chloride, ammonium sulfate, kieserite, and rock phosphate. The herbicide glyphosate is used mainly to make the circles around the plant. The insecticide acephate is used in a small quantity due to use of integrated pest management, where natural enemies are used instead of pesticides.

The harvest operations start at 3 years of age and continue until the oil palm plantations are 25 years old. Harvesting of ripe FFB is manually carried out every 12 days using a sickle mounted on an aluminum pole. Normally, two fronds beneath the fruit bunch are pruned before harvesting. The pruned fronds are placed in the field between the palm rows for mulching. Detached FFBs are placed by the roadside, collected and disposed in dumpsters, and later taken by truck to a palm oil mill.

Replanting of oil palm is carried out after 25 years due to difficulty in harvesting tall palms and to low FFB yield. So, the palms are felled, chipped, and left in the plantation as a nutrient source for the new palm plants.

2.2.2 CPO production

In the palm oil mill, the FFBs are transferred into the sterilizer. The fruits are sterilized by steam (135°C) under a pressure of 3 kg cm⁻² for 80–90 min. The sterilization process avoids loosens of the individual fruits from the bunch and also deactivates the enzyme which the breakdown of the oil into FFA.

The sterilized FFBs are sent to a thresher where the fruits are separated from the bunch. The empty fruit bunches (EFBs), which are abundant, may be used to produce steam and power, and the ashes used as fertilizers [13]. However, in the Agropalma farm, the EFBs also are applied on the organic plantations as organic fertilizer.

The fruits from the thresher are then sent to a digester that converts the fruits into a homogeneous oily mash by means of a mechanical stirring process. The digested mash is then pressed using a screw press to remove the major portion of the CPO. At this point, the CPO comprises a mixture of oil, water, and fruit solids, which are screened through a vibrating screen to remove as much solids as possible. The oil is then clarified in a continuous settling tank whose decanted CPO is then passed through a centrifugal purifier to remove remaining solids and then sent to

the vacuum dryer to remove moisture. The CPO is then pumped to storage tanks before it is sent off to the refining process.

The nuts with the pressed mesocarp fibers are separated at the fiber cyclone and then cracked to produce kernels and shells. The kernels are shipped to kernel crushing plants to be processed into crude palm kernel oil (CPKO), while the shell and pressed mesocarp fiber are used as boiler fuel.

The main solid residues from the milling process are EFBs, pressed mesocarp fiber, shell, and boiler ash, while the liquid waste is palm oil mill effluent (POME) (**Figure 2**). In the studied plantations, the POME is conveyed from the mill and disposed in anaerobic ponds and later is used for palm tree irrigation purposes. All the residues from the palm oil extraction process are reused in the oil palm cultivation (EFB, ashes, and POME) or palm oil mill (fiber and shell).

2.2.3 Transportation of CPO from palm oil mill

The CPO stored in tanks is transported by trucks to the barge docks 24 km away from the mills and then is taken by barge to the refinery located 200 km from the farm. Each barge carries 1100 t of CPO. Besides being cheaper due to geographical conditions of the palm oil mill, the CPO transportation by the waterway is easier than it is by road in the region of study.

2.3 Scope definition and data collection

The scope of this study comprised since the stage of oil palm seedling production until the transportation of CPO. Inventory data included the main steps of the palm oil supply chain: agricultural production of FFB, extraction of CPO, and transportation of CPO to a refinery. We considered the year of 2009 (January 1 to December 31) to evaluate the carbon footprint of CPO production and transportation at Agropalma farm. In this study, the functional unit (FU) is 1 t of CPO.

We evaluated the GHG emissions related to seedlings production, planting and cultivation of juvenile and mature oil palm plantations, considering a FFB yield of 21.2 t ha⁻¹. The study measured direct and indirect emissions from the use of fuels, fertilizers (i.e., nitrogen, phosphorous, and potassium) and defensives in the production system.

The GHG emissions from industrial processes (by the use of fossil fuels, bio-fuels, biomass, and electricity) and FFB transportation from the field to the palm oil mill (by the use of fossil fuels) were calculated. In addition, we evaluated the GHG emissions from CPO transportation by trucks to the barge docks and then to the refinery. The GHG sources associated to inputs and outputs from the palm oil production, extraction, and transportation are described in **Figure 2**. The input data used to calculate the GHG emissions are listed in **Table 1**. **Table 2** presents the emission factors (EFs) used in this study.

The international standards ISO 14040 and ISO 14044 on life cycle assessments were used in this study to determine the GHG emissions from CPO production based in the methodology proposed by IPCC [18]. When allocation could not be avoided in the treatment of coproducts and residues, the resulting emissions of a process were portioned between its different products in a way that reflected the underlying physical relations between them. The rationale in using mass allocation is that physical portioning is most consistent as it contains the least uncertainties. According to the production at Agropalma in 2009, the weight allocation was 92% of CPO and 8% of PKO. To measure GHG emissions, we have used the inputs presented in the inventory data (**Table 1**) and their respective emission factors (**Table 2**). The EFB and POME are used in the plantations as fertilizers, while the

GHG source	Production stage		
	Agricultural	Industrial	Transportation
Nitrogen (N)	362	—	—
Phosphate (P)	256	—	—
Potassium (K)	3634	—	—
Pesticides (L)			
Glyphosate	52,745	—	—
Organophosphate	6678	—	—
Fossil fuel (L)¹			
Diesel	3,708,216	854,458	365,909
Gasoline	124,834	64,476	—
Energy			
Electricity energy (kW/h)	—	1,685,636	—
Biomass (fiber + shell) (t)	—	80,064	—
Residue			
POME at anaerobic ponds (m ³)	—	693,193	—

¹The quantities of biodiesel and ethanol mixed in diesel and gasoline, respectively, were computed.

Table 1.
Fertilizers, pesticides, fossil fuel and energy inputs, and waste generated in the crude palm oil (CPO) production in Pará State, Brazil.

Source	Unit	Emission factor	Reference
Fuel			
Diesel	kg CO ₂ /L diesel	3.11	[14]
Gasoline	kg CO ₂ /L gasoline	2.85	[14]
Ethanol	kg CO ₂ /L ethanol	0.46	[15]
Biodiesel	kg CO ₂ /L biodiesel	0.39	[15]
Fertilizer			
Nitrogen	kg CO ₂ /kg N	3.14	[16]
Phosphate	kg CO ₂ /kg P	0.61	[16]
Potassium	kg CO ₂ /kg K	0.44	[16]
Electricity			
2009 (medium value)	t CO ₂ /MWh	0.0245	[17]
Herbicide			
Glyphosate	kg CO ₂ eq/kg A.I. ¹	15.95	[14]
Insecticide			
Organophosphate	kg CO ₂ e/kg A.I.	7.68	[14]
Residues			
POME at anaerobic ponds	kg CO ₂ e/kg DQO	5.00	[14]
Biomass (fiber + shell)	kg CO ₂ e/t	22.53	[18]

¹A.I., active ingredient.

Table 2.
Emission factors used to calculate the GHG emissions from crude palm oil (CPO) production in Pará State, Brazil.

pressed fiber and shell are burnt as fuel in the palm oil mill boiler. Nevertheless, the savings for the use of solid residues and POME are not included in this study.

Based on the input data, it was possible to estimate GHG emissions in terms of equivalent CO₂ (CO₂-eq). Emissions of N₂O and CH₄ are compared based on the global warming potential (GWP), since CH₄ and N₂O have a GWP 25 and 298 times larger than CO₂, respectively [18].

3. Results and discussion

3.1 Total GHG emissions

The total GHG emissions resulting from the production of FFB, extraction and transportation of CPO were 112,825 t CO₂-eq (**Figure 3**). The main source of GHG was the management of POME, followed by fertilizer application, fuel combustion, pesticide application, and electricity use. The high CH₄ emissions in the anaerobic ponds, when converted into CO₂-eq represented 66.5% of the total emissions. The use of fertilizers and fuels contributed to 17.9 and 15.1% of the total emissions, respectively. The application and electricity use represented less than 1% of the total GHG emissions (**Figure 4**).

The highest GHG amount emitted from POME is related to CH₄ emissions in the anaerobic ponds. The anaerobic ponds located in Agropalma farm are over 2 m deep and the POME has a large amount of C available and, consequently, high COD (chemical oxygen demand). In this study, the COD had an average of 21.65 kg m⁻³, which is considered a high value by the standards of the Intergovernmental Panel on Climate Change [18] for effluents generated in the vegetable oil industry.

Similar results were found by Choo et al. [19] determining the GHG contribution by subsystems in the oil palm supply chain at Malaysia. The highest emissions were associated to POME without biogas capture. After POME disposal into the ponds, the CH₄ content is higher in the outlet region [20]. This is explained by excess concentration of organic matter in the inlet region that would influence the methanogenic activities [21]. As a result, lower CH₄ and higher CO₂ are emitted from the inlet region.

The fertilizers applied in the seedlings production and oil palm plantations resulted in the second largest GHG emission source. It is important to notice that GHG emissions are released both during the industrial production of fertilizer and through the application of these fertilizers on the field. The cultivation of oil palm requires high inputs of nitrogen fertilizer, which can create high soil emissions due to a conversion into N₂O [22].

The oil palm cultivation in Agropalma farm uses small amount of pesticides, resulting in low GHG emissions due to the use of these products (**Figure 3**). In 2009, glyphosate (herbicide) and acephate (insecticide) were used, so that GHG emissions were lower than other results previously reported in Malaysia [13, 19] and in Brazil [12].

The measured fuel combustion was related to agricultural operations, FFB transportation, extraction and transportation of CPO to a refinery. According to previous studies [13, 23], GHG emissions associated to use of diesel in plantations, internal transport and machinery are in order of 180–404 kg CO₂-eq ha⁻¹ yr⁻¹. If the FFB yield is set at 21.2 t ha⁻¹, the total emissions would be in order of 8.5–19.1 kg CO₂-eq/t FFB. We found a total emission of 23.08 kg CO₂-eq/t FFB and this value can be attributed to the highest number of mechanized operations at Agropalma farm compared with the most part of palm oil companies in Southeast Asia. Moreover, we also include the emissions from the combustion of fibers and

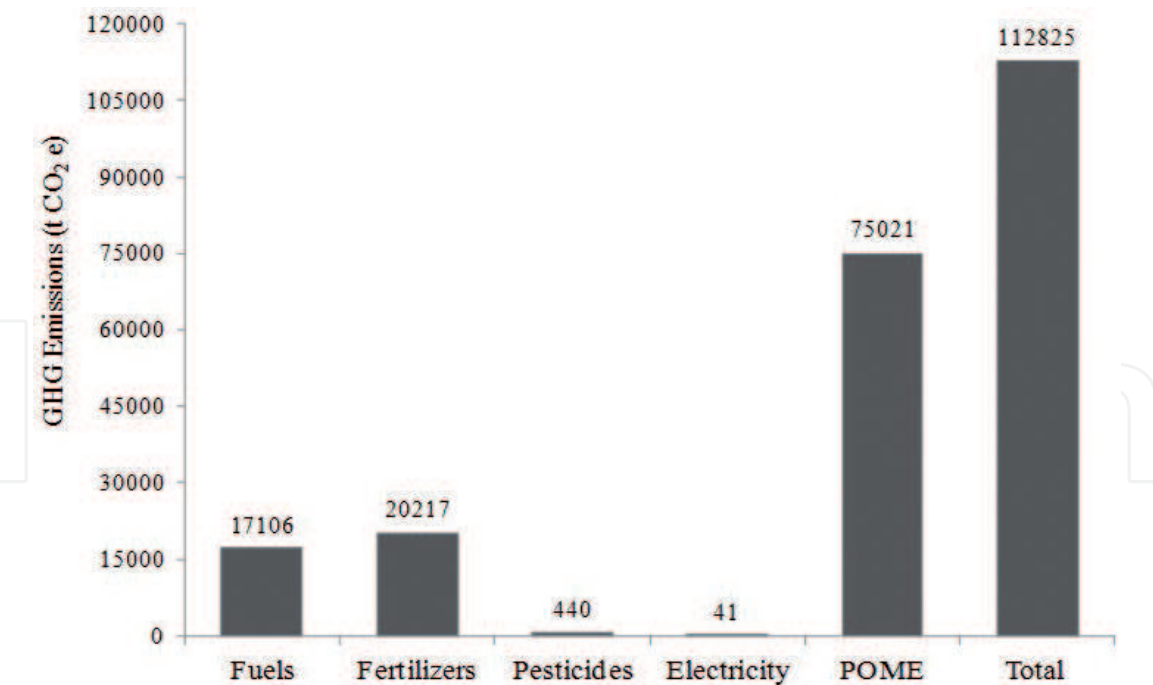


Figure 3.
Total GHG emissions (t CO₂-eq) in 2009 from crude palm oil production in the Brazilian Amazon region.

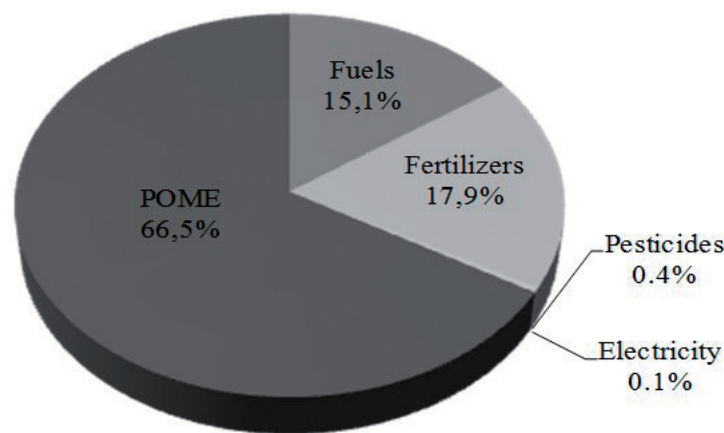


Figure 4.
Partition of total GHG emissions from crude palm oil production in the Brazilian Amazon region.

shells used in the boilers, which represent 10.5% of total emissions from the use of fuels.

The electricity is derived from hydroelectric power plants, which are considered a clean energy source. So, the GHG emissions were low, in agreement with previous results reported by Souza et al. [12]. The use of biomass (shell and fiber) in the boilers also contributed to the reduced use of electricity. In Malaysia, Yee et al. [24] have reported that from the amount of energy generated from the fibers and shell, about 55–77% is being utilized in the milling processes in the form of heat (steam) and power (electricity). The combustion of coproducts in high-efficiency boilers and turbines for power production reduces life cycle GHG emissions even when the most part of the electricity consumed comes from hydroelectric power plants [12].

3.2 GHG emissions in the agricultural phase

The agricultural phase (seedling production, juvenile and mature plantations) contributed to 28% of the total GHG emissions in the palm oil production, emitting

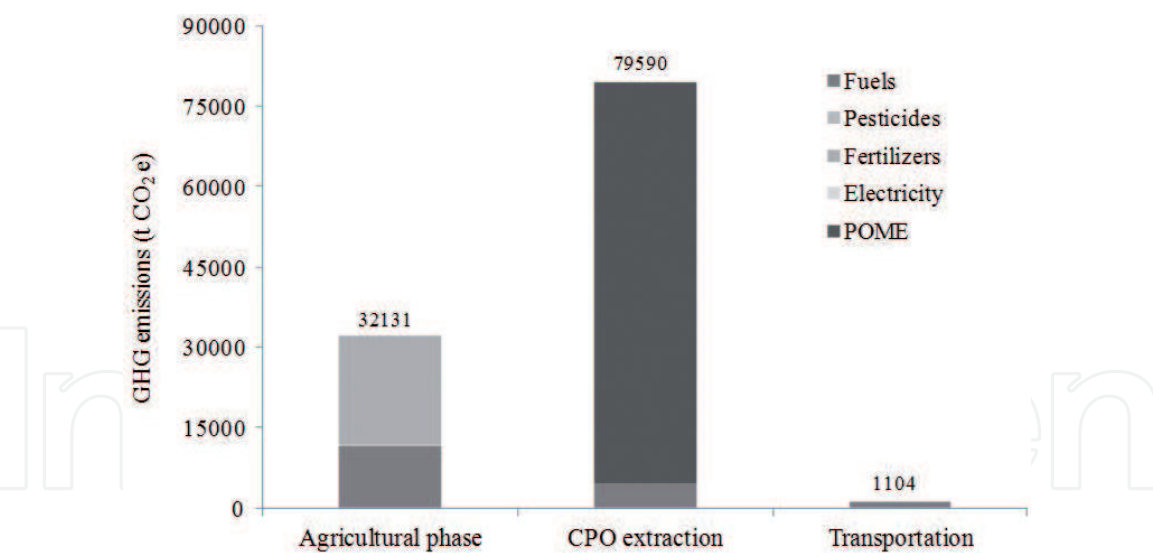


Figure 5.
GHG emissions (t CO₂-eq) from agricultural phase, CPO extraction and transportation in the Brazilian Amazon region.

32,131 t CO₂-eq in 2009 (**Figure 5**). The use of fertilizer was the main source of GHG emissions, followed by the use of fuels and pesticides. We found that in the production of FFB, 88% of GHG emissions are related to mature crop stage, while 1 and 9% are from the nursery and juvenile stands, respectively (**Figure 6**). These results are in agreement with other studies analyzing the GHG emission sources in the agricultural phase of oil palm production [23, 25].

In the oil palm nursery, the inputs of fertilizers and pesticides are relatively low compared to the other stages, and the activities for the seedlings cultivation are performed manually. The use of fuel is required only for the seedlings transportation and irrigation. So, this step contributed to insignificant amounts to the GHG emissions, corroborating with the results reported by Choo et al. [19].

In the oil palm plantations (juvenile and mature stands), the fertilizer application rate is dependent on a number of factors including yield potential, age of palm plant, nutrient balance, field conditions, and soil types. In 2009, the medium amount or

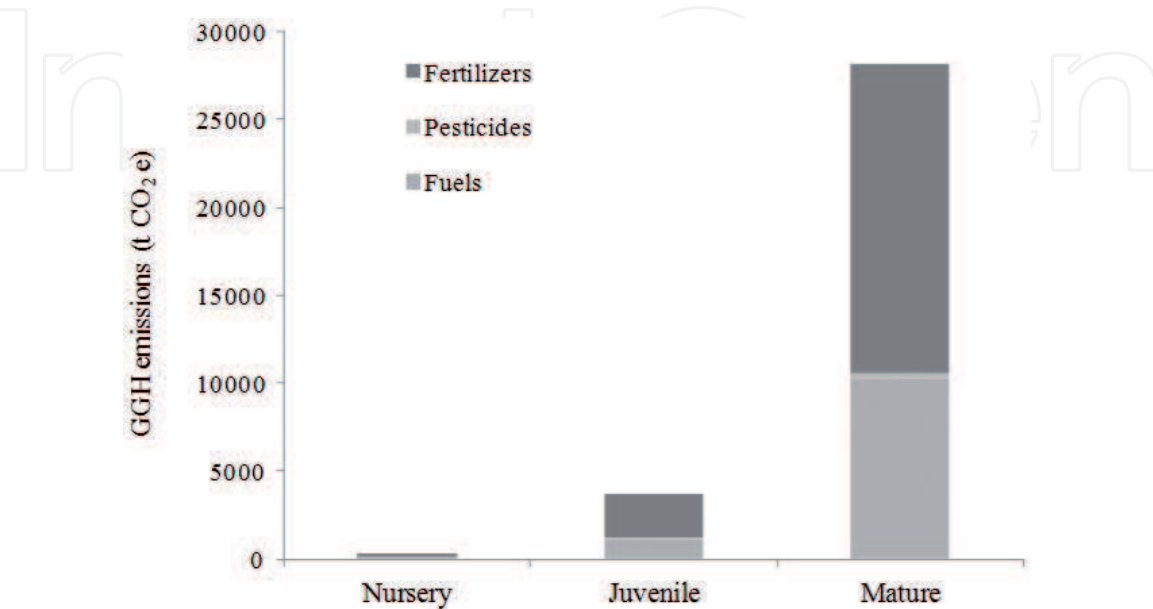


Figure 6.
GHG emissions (t CO₂-eq) in the agricultural phase of CPO production in the Brazilian Amazon region.

fertilizer applied for juvenile stands (1–3 years) was 36 kg N ha⁻¹, while in the mature stands (FFB production areas), it was 48 kg N ha⁻¹. We found that the use of fertilizer contributes to 63% of GHG emissions in the agricultural phase, agreeing with previous results reported by Yee et al. [24], Souza et al. [12], and Choo et al. [19].

The application of fertilizers and harvesting operations and the transportation of FFB from the field to the mill require the use of fossil fuels and biofuels. GHG emissions from the use of fossil fuels and biofuels accounted for 36% of total GHG emissions in the agricultural phase.

3.3 GHG emissions in the CPO extraction

In the palm oil milling stage, the GHG emissions were from the use of fuels, electricity, and disposal of POME. We observed that CPO extraction was the largest source of GHG emissions (71%) in 2009 (Figure 5).

As mentioned before, the use of fuels in the palm oil mill is represented by fossil fuels, biofuels, and residues of CPO extraction (fiber and shells). In the Agropalma farm, 80,000 t of fiber and shells were used as fuel in 2009. Normally, biomass is used for heat and/or power production through direct combustion. Yee et al. [24] have reported that palm oil mills in Malaysia are self-sufficient in terms of electricity consumption due the use of fiber and shells as source of power. The use of fossil fuels blended with biofuels, and residues of CPO extraction contributed to 3.4 and 2.3% of the total GHG emissions (Figure 7).

The CH₄ from POME in anaerobic ponds represented 94.3% of the total GHG emissions in the palm oil mills. In Malaysia, Shirai et al. [26] and Yacob et al. [27] have reported that the CH₄ composition was between 35 and 45% for the anaerobic treatment of POME, while Yacob et al. [20] recorded an average of 54.4%. After 1 year of observation at the anaerobic ponds, these authors observed that CH₄ emission pattern is governed by the oil palm seasonal cropping and mill activities. In this study, we used the default value proposed by IPCC, so the continuous monitoring is necessary to obtain the seasonal fluctuations in GHG emissions.

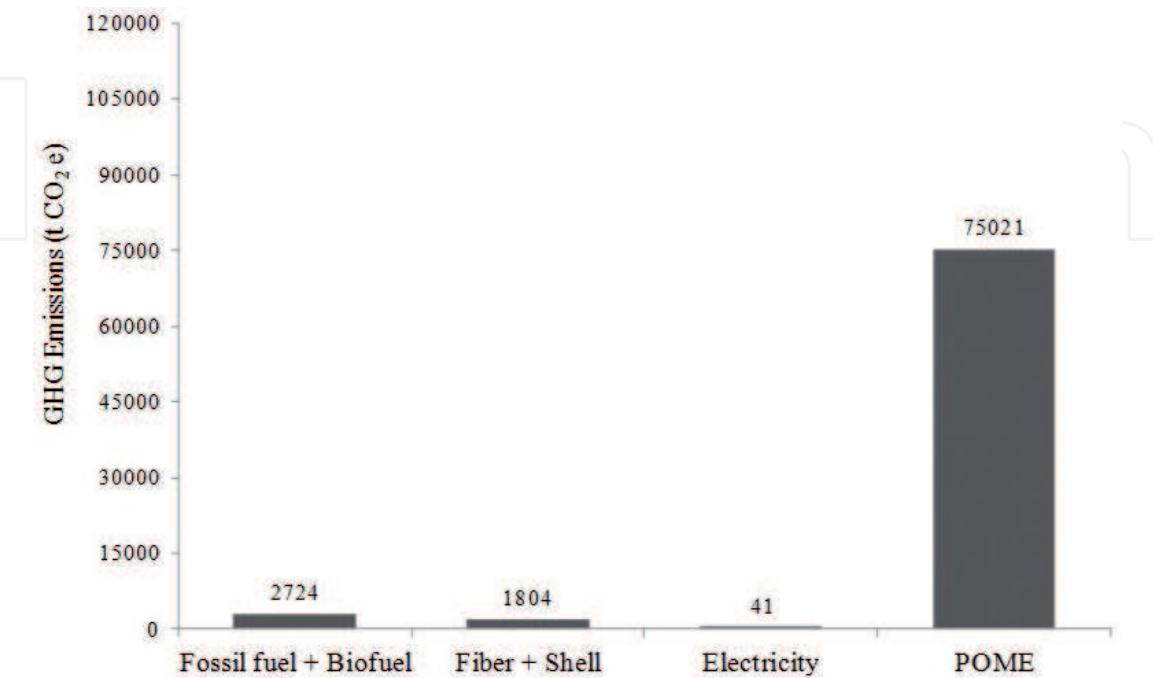


Figure 7. GHG emissions (t CO₂-eq) in the palm oil milling stage in the Brazilian Amazon region.

Determining the GHG emissions by subsystems in the oil palm supply chain, Choo et al. [19] also reported the highest emissions associated to POME production. Their results showed reduction of GHG emissions from oil palm mill when the CH₄ was captured. Reijnders and Huijbregts [23] reported a reduction on GHG emissions of about 0.15 t CO₂-eq/t CPO produced when 95% of control efficiency for the treatment of POME is assumed.

3.4 GHG emissions from the CPO transportation

The fuel combustion during the CPO transportation from the palm oil mill to the refinery represented 1% of the total GHG emissions in 2009 (**Figure 5**). As mentioned before, the transportation of CPO from oil palm mill to refinery at Agropalma farm is performed by barge where one roundtrip carries 1100 t of CPO and consumes 3500 L of diesel. Since 105 roundtrips were performed in 2009, the GHG emissions from the use of diesel at Agropalma farm during the transportation of CPO were 1104 t CO₂-eq.

According to Majer et al. [22], the GHG emissions from transportation process typically represent only a small share of the overall balance results in the biodiesel production. In contrast to our results, Choo et al. [19] reported higher GHG emissions from the transportation process in Malaysia due the distance of oil palm mill until the refinery. The authors point out those GHG emissions could be reduced by improving transport logistic by routing delivery of CPO, for the shortest distance between the supplier and the refinery.

3.5 Carbon footprint of CPO production and transportation

In the palm oil mill, CPO and KPO are obtained as main products among the several by-products from the extraction process (**Figure 2**). Several studies have reported the GHG emissions considering the production area or the quantity produced [12, 19, 23, 28]. We calculated the GHG emissions related to CPO production using mass allocation based on a specific agricultural year. The carbon footprint was calculated considering the GHG emissions per t of CPO produced at Agropalma farm. In 2009, the CPO and KPO production were 130,210 and 11,205 t, respectively.

Considering the agricultural production of FFB, CPO extraction, and CPO transportation from the mill to the refinery, we found an emission of 0.79 t CO₂-eq/t CPO produced at Agropalma farm in 2009. As we mentioned before, 66.5% of the total emissions are related to management of POME in the anaerobic ponds. The C footprint of CPO can be reduced significantly since oil palm and palm oil processing wastes are used to replace the input of fossil fuel in palm oil processing stage [29]. This can be combined with a reduction in the amount of CH₄ emitted from oil palm processing waste [23]. The company could adopt the system of CH₄ capture from POME and use it as electricity or power source [19, 20].

3.6 Comparative GHG emissions in CPO production

Our study is the first to approach carbon footprint considering the different stages (agricultural, industry, and transportation) of CPO production in Brazil. We found that industry is the main source of GHG emissions (71%) due the management of POME in anaerobic ponds. Another study in Thailand [6] has reported similar results, and the GHG emissions in CPO extraction (industry) allocated by energy value were 0.55 t CO₂-eq/t CPO. But contrary to what was observed in this study, the authors have considered the carbon stocks.

Determining the GHG contributions by subsystems in the oil palm supply chain using the LCA approach in Malaysia, Choo et al. [19] have reported that the production of 1 t of CPO in a mill without and with biogas capture emitted 0.97 and 0.51 t CO₂-eq, respectively. As we found in this study, the contribution of nursery subsystem was found to be minimal, and in the plantation subsystem the major sources of GHG were from nitrogen fertilizers.

Regarding the soil GHG emissions in Indonesian oil palm plantations, Rahman et al. [5] have reported that the use of inorganic fertilizers led to significantly higher N₂O emissions. Therefore, as we found in this study that the use of fertilizers accounted for 63% of GHG emissions in the agricultural phase, the use of organic amendments (empty fruit bunches, enriched mulch, and pruned oil palm fronds) can be an option for reducing GHG emissions.

3.7 Mitigation of GHG emissions and opportunities to achieve CO₂ sequestration

The GHG emissions have been reported along the palm oil production chain from the roundtable on sustainable palm oil (RSPO) [30]. Methane (CH₄) emissions from wastewater in open ponds at the milling phase and nitrous oxide (N₂O) emissions from nitrogen fertilizer application in the cultivation phase are the most related sources of GHG emissions [31, 32].

In this study, the C footprint associated to CPO production was about 0.79 kg CO₂/kg CPO and the main source of GHG emissions is associated to management of POME in the anaerobic ponds. Previous study in Thailand also has reported that wastewater treatment and empty-fruit-bunch disposal in mills are a main source of CH₄ emissions and cause global warming, with up to 47 and 45% of total global warming impact [33]. So, the effluent treatment in the anaerobic ponds and the combustion of CH₄ during anaerobic decomposition [34] are cited as viable strategies to reduce the GHG emissions at the milling phase.

According to Chai et al. [35], energy content in wastewater, in the form of chemical oxygen demand (COD), is usually converted into CO₂ or CH₄ and biosolids through either aerobic treatment or anaerobic treatment. Therefore, decreasing the degree of aerobic treatment and maximizing energy recovery from CH₄ and biosolids are crucial to lower carbon footprint. An efficient anaerobic digestion could contribute to the decrease of the degree of subsequent aerobic treatment, by removing certain amount of COD and reducing CO₂ emissions, and recover energy from CH₄ by anaerobic digestion.

When the POME is converted into biogas (CH₄) through a gasification process and then used to fuel gas engine and generate electricity, it is possible to reduce the environmental impact of CPO production. In addition, other recent technological advances have turned POME to useful sustainable feedstock that can be used to produce valuable by-products like biohydrogen [36] and biomethane [37].

Regarding the oil palm plantations, there are four main steps that contribute to GHG emissions: soil preparation, fertilizer management, weed control, and FFB transportation. In this study, we reported that the use of fertilizer was the main source of GHG emissions, followed by the use of fuels and pesticides. The use of EFB for infield application in young and mature palm areas has been used in the management of soil nutrients and organic matter and promoting the increase of organic carbon in the soil over time [38, 39]. So, the continuous use of EFB as mulching could play a significant role in reducing CO₂ emissions into the atmosphere through soil C sequestration [39].

As also mentioned before, the use of *Pueraria phaseoloides* as cover crop can also reduce the use of nitrogen fertilizers in the young and mature palm plantations.

Previous study has reported that the use of legumes contributes about 150 kg nitrogen ha⁻¹ year⁻¹ to the system through biological nitrogen fixation [40]. So, the use of EFB and legumes in the agricultural phase can reduce the mineral fertilizer demand and consequently minimize GHG emissions.

In the Brazilian Amazon region, the maintenance of native vegetation and the use of degraded areas to introduce new oil palm plantations can promote environmental benefits to commercial farms, reducing the GHG emissions. Brazilian government approved a bill to expand 4.3 million ha of previously deforested lands to oil palm plantations [41]. Pará State is intensively studied because the majority of the land deemed suitable for oil palm expansion by the government is located in this state. According to Yui and Yeh [42], the encouragement of oil palm plantations on deforested lands could drastically reduce the conversion of forest land, thus reducing GHG emissions from deforestation.

4. Conclusions

Considering the production of seedlings and FFB, the extraction and transportation of CPO in a Brazilian commercial farm at Amazon region, it emitted 0.79 t CO₂-eq/t CPO produced in 2009. Main contributing factor to GHG emissions during the cultivation step is the use of industrial fertilizers, which accounted for 17.9% of the total GHG emissions mainly due the high input of nitrogen. The management of POME from palm oil mill is the main source of GHG emissions to the atmosphere, representing 66.5% of the carbon footprint during the evaluated period. Regarding the use of fuels in all evaluated stages, they accounted for 15.1% of the total GHG emissions.

The POME treatment in the anaerobic ponds and the use of CH₄ for steam or electricity production and the use of EFB and legumes in the agricultural phase are cited as the main strategies to reduce the GHG emissions in the palm oil production system.

Our results may be used to encourage new researches and improve the life cycle assessment and the measurements of GHG emissions associated to palm oil production chain in Brazil and other regions of South America.

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