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Renewable energy for environmental protection: Life cycle inventory of Nigeria's palm oil production

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ABSTRACT

Energy consumption and associated greenhouse gas (GHG) emissions will increase significantly in the developing world. Scaling up bioenergy use and reducing GHG emissions is vital to achieving the Nationally Determined Contributions and advance the greener economy. This study investigated three types of palm oil processors to support technology advancement and renewable energy transition in the African oil palm industry. We compiled gate-to-gate life cycle inventories of large-scale, semi-mechanized, and smallholder processors of oil palm fresh fruit bunch in Nigeria. The inventory includes materials and energy inputs to the systems and outputs and emissions to the environment. The inputs are diesel, water, electricity, empty fruit bunch, palm kernel shell and mesocarp fibre for a functional unit of one tonne of fresh fruit bunch, while the outputs are crude palm oil, palm kernel, and all emissions to air and soil. Carbon dioxide (CO₂) and dinitrogen oxide (N₂O) emissions were 47% and 73% more in smallholder mills than in large-scale mills. Semi-mechanized mills produced 73% more N₂O than large-scale mills. In contrast, large-scale mills emit 71% more methane (CH₄) than smallholder and semi-mechanized mills. The study reveals critical hot spots of GHG emissions from different processors of Nigeria's oil palm industry. These findings will contribute to supporting policymaking, developing technology, and promoting bioenergy use within and outside the industry as an essential strategy for mitigating climate change.

1. Introduction

Energy consumption and associated greenhouse gas (GHG) emissions are expected to considerably increase in the developing world (Souza et al., 2017), given the projected social and economic development. At the same time, climate models suggest that Africa's climate, for example, will become more variable with high levels of uncertainty, resulting in potentially significant economic impacts across the continent (Martens et al., 2021). While bioenergy offers a greener alternative to fossil fuel-based economy, the use of biomass-based renewable energy in production remains rare. It calls for more efforts in research and technology advancement towards a green and carbon-neutral economy. Scaling up the use of renewable energy and reducing GHG emissions are essential strategies to achieve the Nationally Determined Contributions (NDCs) and advance Sustainable Development Goals (SDGs) of the United Nations.

An essential step towards climate change mitigation is to map the significant sources of GHG emissions. A comprehensive inventory will allow the identification of opportunities to adopt necessary measures

towards reducing GHG emissions, particularly in energy-intensive industries that have significant environmental impacts. Nigeria is the fifth-largest producer of palm oil worldwide after Colombia, Thailand, Malaysia, and Indonesia (FAOSTAT, 2021). As the key global players, Indonesia and Malaysia have over 17.3 million hectares of oil palm plantation (Gozan et al., 2018). In comparison to other oil crops, oil palm (*Elaeis guineensis*) contributed 34% of the global vegetable oil market in 2017; it thus accounted for the most traded oil crop in monetary terms and yield eight times more than soybean (Mayes, 2020; Nurrochmat et al., 2020; Schmidt & Weidema, 2008). This position of oil palm amongst other oil crop is particularly very important because of the increasing need to meet global oil demand. To transform the palm oil industry into a less carbon-intensive and greener economy, we urgently need to estimate GHG emissions, investigate the impacts of palm oil processing, and develop a circular economy strategy where feasible.

Oil palm tree produces fruits in bunches known as the fresh fruit bunch (FFB). Palm fruit consists of palm oil bearing mesocarp that encloses palm nut. The seed in the palm nut contains palm kernel oil. Empty fruit bunch (EFB), mesocarp fibre (MF) and palm kernel shell

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(PKS) are the solid biomass by-products generated during the processing of FFB. FFB solid biomass (EFB, MF and PKS) is commonly used, especially in large-scale palm oil mills, in firing boilers for steam generation. In addition to the solid wastes, palm oil mill effluent (POME) is the liquid wastes generated from FFB processing, a mix of the colloidal suspension composed of water, oil, and solids. Oil and grease, chemical oxygen demand (COD), and biological oxygen demand (BOD) are the POME's pollutant indicators. A direct discharge of POME to the environment can cause oxygen depletion in water bodies and soil biodiversity loss due to contamination (Ho et al., 2021).

Large-scale palm oil producers in Nigeria and other countries often use PKS and MF, and sometimes EFB for heat and power generation, which to a large extent ensures independence in energy demand. Conversely, the small-scale processors, which make up more than 80% of the palm oil processors in Nigeria, rely heavily on diesel power while making very little use of the biomass wastes generated in the mills (Ohimain & Izah, 2014a). Consequently, the bulk of solid wastes are left unused while more carbon dioxide (CO₂) is emitted to the atmosphere due to diesel burning. Such operation limits the small-scale processors' ability to process the FFB on time, which is vital to reducing palm oil's free fatty acids and increasing its market value. The small-scale processors can be classified into semi-mechanized and smallholder processors, based on the technology applied in palm fruit processing.

Several studies have reported life cycle inventory and life cycle assessment in the oil palm industry, including composting of EFB, and anaerobic digestion of POME. Baron et al. (2019), Stichnothe & Bessou (2017), Muhamad et al. (2014), Norhasmillah et al. (2013), Muhamad et al. (2012), Stichnothe & Schuchardt (2011), Tan et al. (2010), Vijaya et al. (2010), and Vijaya et al. (2008) highlighted the importance of proper management of biomass in reducing GHG emissions in the oil palm industry. Tan et al. (2010) carried out a life cycle assessment of refined palm oil production and fractionation. They identified the refining of crude palm oil to refined palm olein and palm stearin, followed by boiler fuel combustion system as the GHG emission sources. Life cycle assessment of oil palm seed production (Muhamad et al., 2014) and life cycle assessment of oil palm seedling (Muhamad et al., 2012) have been reported. Muhamad et al. (2012) concluded that the polybags used to grow the seedling and the fungicide for pathogenic fungi control constitute more to fossil fuel depletion, while Muhamad et al. (2014) identified fossil fuel, respiratory inorganics, and climate change as the major impact category.

Vijaya et al. (2010) identified fossil fuels consumption in the production of fertilizer and diesel use in transportation and harvesting as primary contributors to the impact categories in a life cycle assessment of crude palm oil production. Stichnothe & Schuchardt (2011) carried out a life cycle assessment of two palm oil production systems where the residues are either treated or not. The results showed composting of EFB reduces GHG emissions compared to dumping. On the other hand, Vijaya et al. (2008) documented a life cycle inventory of palm oil production in Malaysia. The studies focused on large-scale processors of FFB, which did not account for the effects of different levels of technology on emissions in the industry, particularly in parts of the world where local technologies are commonly applied in processing FFB. For instance, Stichnothe & Schuchardt (2011) mentioned the importance of cleaning the exhaust gas to reduce eutrophication, acidification, and toxicity. It highlighted the difference between the availability and non-availability of technology for cleaning exhaust gas. Additionally, Anyaoha et al. (2018) and Izah & Ohimain (2015) have reported the different FFB processors in Southern Nigeria. However, most of the published works focused on large-scale palm oil production. There is still a significant lack of data and knowledge about the varying environmental outputs of the small-scale processing systems and the comparison with large-scale systems, notably contrasting level of technologies. Understanding the environmental flows and emissions of the three technological levels (i.e., large-scale, semi-mechanized, and smallholder processors) is critical to identifying opportunities to reduce the

Table 1

The material mass balance of fresh fruit bunch. The bold figures are applied to the inventory of a tonne of fresh fruit bunch for each mill.

Parameter	Ohimain et al. (2013a)	Smallholder	semi-mechanized	Large-scale
Empty fruit bunch/chaff	301.8	301.8	301.8	301.8
Mesocarp fibre	243.3	243.3	243.3	243.3
Palm Kernel	60.9	60.9	60.9	60.9
Palm kernel shell	118.6	118.6	118.6	118.6
Crude palm oil	140.6	153.35	153.35	188.3
Water in mesocarp	105	105		
Water in nut	27.2	27.2		
Palm oil mill effluent		153.83	535.73	653.33

environmental effects of Nigeria's palm oil industry, which will also provide a reference for other African countries.

Life cycle assessment (LCA) is an essential tool for assessing the environmental burdens of processes, services, and products, enabling identifying inputs from and outputs to the environment. The four phases of LCA are (i) definition of the goal, scope, functional unit, and boundary conditions; (ii) life cycle inventory (LCI); (iii) life cycle impact assessment (LCIA); and (iv) interpretation of results. The outputs in LCI are usually emissions to air, water, and soil.

This study aims to compile the life cycle inventories of the three typical oil palm industry systems in Nigeria. The study results will provide evidence to support technology advancement and renewable energy transition in the African oil palm industry, ultimately contributing to green economy transition and sustainable development.

2. Materials and method

2.1. Scope and goal definition

A gate-to-gate life cycle inventory is applied to the three technological levels of Nigeria's oil palm industry. The system boundary covers the processing of FFB, from reception of the bunches to production of palm oil, and the biomass and POME generated. The oil palm plantation stage was excluded because we considered it an identical process in the comparative studies. The functional unit is 1 tonne of fresh fruit bunch processed to crude palm oil. The data used in this study were obtained from scientific publications, publicly available information, direct communication/site visit with stakeholders in the study area of South Eastern Nigeria. Technical assumptions were made based on literature sources in the absence of data; emphasis was placed on local conditions to the best of our knowledge. We assumed the use of only diesel and no petrol in the mill.

The inputs include FFB, diesel, biomass, and water, while the outputs are all emissions to the environment, crude palm oil and palm kernel, which are co-products. The smallholder, semi-mechanized and large-scale processors were considered separately. The detailed step by step calculations in the life cycle inventories are presented in the following sections. Emission from capital goods, including building, machinery, and means of transportation and overhead, were not included in the inventory calculation. Available data for capital goods for the large-scale mills are very uncertain and does not have significant effects on results (Schmidt, 2007).

The material mass balance of 1000 kg of FFB was estimated based on the study of Ohimain et al. (2013a), which is a significant contribution to the material mass balance of FFB in South East of Nigeria. Ten study sites were reported; the average values were applied as shown in Table 1. From communication with processors at Ohaji Imo State Nigeria, smallholder mills produce 184.6 litres of crude palm oil per t of FFB, which was estimated as 166.1 kg (palm oil density = 0.8996 kg/litre) (Esteban et al., 2012). The average of 166.1 kg and 140.6 kg

Fig. 1. System Boundary (dotted lines) for processing 1 tonne of fresh fruit bunch in the Smallholder mills.

Fig. 2. System boundary (dotted lines) for processing 1 tonne of fresh fruit bunch in the semi-mechanized mills.

(Ohimain et al., 2013a) was applied for the small-scale mills. Data from a large-scale processor (SIAT Nig Ltd) located in the study area was applied for crude palm oil yield. The likelihood of variation was considered in the material mass balance. These variations are usually due to the different oil palm varieties (psifera, dura, and tenera) available in the study area. The detailed material mass balance is shown in Table 1. Figures 1, 2 and 3 represent the product flow with system boundary for processing 1 tonne of FFB in the smallholder system, semi-mechanized and large-scale mills. The processes involve the separation of fruits from the bunch (stripping/threshing), sterilization/cooking of fruits, digestion, oil extraction/pressing, mesocarp fibre/palm nut separation, palm nut cracking, palm kernel/palm kernel shell separation, and crude palm oil clarification (Figures 1, 2, and 3).

2.2. Quantity of water input and wastewater generated

Hartley (1988) reported 300 kg of wastewater from palm oil clarification, 175 kg of sterilizer condensate (wastewater) and 140 kg of wastewater from palm kernel/shell separation per t FFB. These are the primary sources of POME. Therefore, a total amount of 615 kg/t FFB was

suggested. Singh (1999) and Ma et al. (2004) reported 670.0 kg/t FFB and 675.0 kg/t FFB of POME/t FFB, respectively. An average of these three values (653.33 kg) was applied as the total POME or wastewater produced by the large-scale mill (Table 1). Ohimain & Izah (2014b) reported that about 50 – 79% of the water used in FFB processing end up as POME, which is 64.5% by average and equivalent to 1012.91 kg of water. Yoshizaki et al. (2013) and (2012) reported 1000 kg of water per t of FFB. The average value of 1006.46 kg was applied.

Like the smallholder processors, the semi-mechanized processors sterilize/cook the fruits instead of the FFB. We estimated that the large-scale mill would require 50% more water than the semi-mechanized mill in the sterilization stage and thus more POME. Department of Environment (1999) reported that wastewater from palm nut and palm fibre separation, sterilizer condensate, and clarification wastewater represent 4%, 36%, and 60% of total POME produced in the large-scale mill per 1 tonne FFB, respectively. These values have been applied, but sterilizer condensate is 50% less for semi-mechanized mill. We assumed 50% of sterilizer condensate (36% POME) and subtracted the value from the 653.33 kg above. As reported above 64.5% of water ends up as POME. Therefore, the total POME for semi-mechanized was estimated at 535.73

Fig. 3. System boundary (dotted lines) for processing 1 tonne of fresh fruit bunch in the large-scale mills.

Table 2

Biomass utilization by different processors as applied in this study*.

Biomass/processors	Smallholder	Semi-mechanized	Large-scale
Empty fruit bunch	150.9 (150.9)	150.9 (150.9)	Nil
Palm kernel shell	(118.6)	(118.6)	118.6
Mesocarp fibre	121.65 (121.65)	121.65 (121.65)	243.3
Total	272.55 (391.15)	272.55 (391.15)	361.9

*The values in parentheses are open burned while each processor uses others for processing 1 tonne of fresh fruit bunch.

kg (Table 1), representing 830.59 kg of water at 64.5%.

In the smallholder mills, 160 kg of water was estimated for boiling fruits, while 32.0 kg was left as wastewater (personal communication). From the milling operation, 105 kg was estimated as wastewater from the pressed palm fruit (Table 1). Similarly, 16.83 kg of water was estimated for palm kernel shell/palm kernel separation and subsequently discharged as wastewater. The amount lost in mud is considered insignificant. Therefore, the total water input and wastewater output for the smallholder mills were estimated as 176.83 kg and 153.83 kg.

The POME generated in the large-scale mills usually stays in an aerobic pond before discharging into the farm. The inventory covers emissions during the life of POME in the pond. Both aerobic and anaerobic digestion occurs in the pond, leading to the emissions of CO₂ and methane (CH₄), respectively. The average values of CH₄ reported by Nasution et al. (2018), Yacob et al. (2006), and Chavalparit (2006) was applied (6.54 kg). The density of methane was taken as 0.717 g/litre (Andersen et al. 1981, p 119). Schmidt (2007 p 164) reported the values of 0.0862 kg, 0.058 kg, and 0.0015 kg for hydrogen sulphide, ammonia, and dinitrogen oxide (N₂O) emissions per t of POME, respectively. The

Table 3

Moisture content and calorific values of empty fruit bunch, mesocarp fibre and palm kernel shell (Anyaoha et al., 2020).

Biomass/parameter	Carbon content (%)	Ash content (%)	Moisture content % Small-scale	Large-scale
Empty fruit bunch	43.8	4.4	14.4 (17.47)	60*
Mesocarp bunch	52.1	4.8	12.1 (20.84)	40 (19.188)
Palm kernel shell	52.3	1.5	12 (19.98)	12

Calorific values are in parenthesis and measured in MJ/kg. *Aziz et al. (2017),

**Husain et al. (2003).

values per t of FFB have been applied in the inventory.

2.3. Management of solid biomass produced per tonne of FFB

In the smallholder system, only about 50% of EFB/MF produced per t FFB are used to process 1 tonne of FFB during a site visit and from personal communication with the processors. The PKS is dumped and openly burned afterwards. Ohimain & Izah (2014a) presented a summary of EFB, MF and PKS used for boiling in smallholder systems: 17% of EFB; 29% of MF; and 4% of PKS. PKS appears insignificant at 4%. These values represent less than 50% of each fuel and not consistent with the explanation above. On the other hand, Ohimain & Izah (2015) reported that almost all EFB is used for firing boiler by the semi-mechanized processors. This study assumed both EFB and MF are equally used for cooking and firing boiler at 50% utilization in both smallholder and semi-mechanized processing. The remaining biomass (EFB and MF) and PKS were assumed to be disposed by open burning, as reported by Izah & Ohimain (2015). Therefore, in the estimation of emissions in small-scale mills, all biomass was considered to be incinerated in closed and open spaces (Table 2).

Some reported figures on the ratio of MF/PKS used as boiler fuel in the large-scale mill ranged from 25 to 70 kg for PKS and 130 to 157 kg for MF (Chavalparit et al., 2006; Yoshizaki et al., 2012 and Schmidt, 2007). The differences between the given data in Table 2 appear to be significant. The processing of FFB is carried out at the same rate all year round in the large-scale mills. Therefore, we estimated that all MF and PKS produced per t of FFB were used to process a tonne of FFB as reported in Schmidt (2007).

The emissions factors of CO₂, CH₄ and N₂O obtained from IPCC (2019) were used to estimate the GHG emissions from biomass combustion, while other parameters were from EMEP/EEA (2019). Currently, no country-specific emission factors are available for Nigeria, according to TNC (2020). The emission factors were converted to g/kg from g/MJ using combined biomass heating values calculated using equation 1 below for the small-scale (16.59 MJ/kg) and large-scale (13.5 MJ/kg) processors.

The CH₄ emission from the landfilling of EFB was assumed to be the same as EFB in a dumpsite, that is 18 kg CH₄/t EFB (Schmidt, 2007) or 5.4 kg CH₄/t FFB. In this study, only CH₄ emissions at the dumpsite were considered. Stichnothe & Schuchardt (2011) reported that 50% of nutrients in EFB at the dumping site would leach. This was considered and modelled as emissions to agricultural soil.

2.4. Steam produced from biomass combustion

The calorific value (CV) of the mixture of MF and PKS used by large-scale processors was estimated using [equation 1](#) (Husain et al., 2003).

$$CV = \text{Proportional weight} * (1 - \text{percentage of moisture content}) * \text{Component CV (MJ/kg)} \quad (1)$$

The proportional weights of MF and PKS used in the boiler are 67.2% and 32.8% (243.3 and 118.6 kg). The percentage moisture content and component CV are presented in [Table 3](#). Therefore, the mixture's calorific value was calculated as 13.5 MJ/kg. [Equation 2](#) was used to calculate the energy input as 4885.65 MJ.

$$\text{Energy Input} = M_F * CV \quad (2)$$

where M_F is the quantity of biomass consumption per t FFB (361.9 kg).

Similarly, with the ratio of EFB to MF at 51.3:48.7%, the CV of the mixture of EFB and MF used by small-scale processors was calculated as 16.59 MJ/kg following [equation 1](#). The energy input was calculated as 4521.60 MJ following [equation 2](#).

2.5. Electricity required by the mill

The utilization factor of 65.6% was used (Husain et al., 2003). The total heat/power production/t FFB was estimated as 3204.99 MJ at 65.6% of 4885.65 MJ (energy input) for the large-scale processors. Using the average heat to power ratio of 17.9 (Husain et al., 2003), we estimated 3035.41 MJ steam and 169.58 MJ electricity. [Ma et al. \(2004\)](#) reported a steam energy content of 2.604 MJ/kg at 3 bars.

Similarly, in the semi-mechanized processors, total heat/power production per t FFB for the semi-mechanized mill was estimated as 65.6% of 4521.60 MJ or 2966.17 MJ. This value is available only for the sterilization of fruits in semi-mechanized mills.

[Yoshizaki et al. \(2013\)](#), [Yoshizaki et al. \(2012\)](#), [Chavalparit \(2006\)](#), and [Husain \(2003\)](#) reported an average value of 23.75 kWh for electricity to process a tonne of FFB. The value, which is equivalent to 85.5 MJ/t FFB (1 kW = 3.6 MJ) was applied. The share of electricity from energy input of 169.58 MJ (estimated above) is equivalent to 47.11 kWh/t FFB representing an excess of 23.36 kWh/t FFB or 84.10 MJ/t FFB. This energy is usually available for use in other areas within the mill. In most large-scale palm oil mills in Nigeria, administrative buildings and staff residence are not connected to the national grid.

2.6. Diesel consumption

Large-scale mills use diesel generator as an alternative source of electricity when the turbines are not in operation. The consumption of diesel directly in processing FFB was estimated as the amount of diesel used in boiler start-up; [Aziz & Hanafiah \(2020\)](#) reported a consumption of 0.42 litres, while [Vijaya et al. \(2008\)](#) reported a value of 0.51 litre per t FFB. The average value (0.465 litres) was applied as diesel used for boiler start-up. The density and lower heating value of diesel used in this study are 0.84 kg/l and 42.8 MJ/kg ([Frischknecht et al., 2007](#)).

In smallholder mills, the digester's operation, palm nutcracker, and water lifting from water borehole involve diesel consumption. In contrast, the semi-mechanized mills require diesel for FFB stripping, fruit digestion/pressing, fibre separation, palm nut cracking and lifting of water.

In the smallholder mills, consumption of 0.11 litres diesel was estimated for the palm nut cracker's operation per t FFB (personal communication). In comparison, [Ohimain & Izah \(2014a\)](#) reported 0.68 litres for the digester. The values were applied for the digester in smallholder mills, while 0.11 litres was used for the palm nut cracker in smallholder and semi-mechanized mills. [Ohimain & Izah \(2015\)](#) reported a 1.85 litres diesel consumption in semi-mechanized mills for all

the processes stated above except for cracking of palm nut and water lifting.

Most smallholder processors have water boreholes as a source of water for the mills. Diesel consumption was estimated as 0.088 litres for lifting 176.83 kg of water considering a 7 hp electric generator (consumes 1.19 litres of diesel per hour) ([Barrington Diesel club, n.d.](#)) and 1 hp pump (lifts about 40 litres of water in a minute) ([Passiontech Solutions n.d.](#)). Similarly, 0.41 litres of diesel was estimated for semi-mechanized mills for pumping 830.59 litres of water. The total diesel consumed by smallholder processor was estimated as 0.88 litres, while that of semi-mechanized processors was 2.37 litres.

The emissions from the combustion of diesel were estimated using the same procedure in biomass combustion above.

2.7. Ash content

The ash content was estimated using [Eq. \(3\)](#) (Husain et al., 2003).

$$\text{Ash produced} = PW * (1 - \%MC) * \%A \quad (3)$$

where PW is the proportional weight of the fuel, %MC is moisture content, and %A is the ash content of the component fuel.

The proportional of EFB and MF for the small-scale mills, and MF and PKS for the large-scale mill were 51.3:48.7% and 67.2:32.8%, respectively, while 30.32:31.1:38.58% were used for PKS, MF, and EFB as proportional weight in estimating ash content of the mixture in open-burning. The moisture content and ash contents are shown in [Table 3](#).

The values for both smallholder and semi-mechanized mills were estimated as 3.99% for EFB and MF, and 3.13% for EFB, MF and PKS combinations, representing the percentage of ash produced from biomass combustion or incineration ([Figs. 1 and 2](#)). The value for large-scale processors (MF and PKS) was estimated as 2.37% of 362.1 kg or 8.58 kg ([Fig. 3](#)).

2.8. Transportation of materials

The transportation of FFB from the plantations was not considered and is usually part of the LCI of oil palm plantation. EFB substitutes fertilizer in the agricultural stage; the transportation of EFB in the large-scale mill to the plantation sites was also not considered. Only the transportation of diesel was modelled in this study. On average, a 28t lorry would transport diesel for 200 km from a regional storehouse in Nigeria. The total diesel consumed by the large-scale processors, semi-mechanized and smallholder processors was 0.33 kg, 1.99 kg, and 0.74 kg. Therefore, transportation of diesel was estimated as 0.07, 0.40 and 0.15 tkm, respectively.

2.9. Sensitivity analysis

The uncertainties related to the assumptions were assessed in a sensitivity analysis. The sensitivity analysis examined the impact of varying inputs on the outputs. The inputs include diesel, water, electricity, and biomass, while the outputs include all the emissions to the environment. The sensitivity analysis assessed the significance of the assumptions made using the same functional unit of 1 tonne of FFB. For example, diesel utilization in smallholder system for the digestion of fruits ranges from 0.6 to 0.8 litres ([Ohimain & Izah, 2014a](#)). An average of 0.68 litres was used in the baseline above. We estimated -12% and +15% of the range to the average value. We have implemented these differences in a sensitivity analysis for diesel consumption in smallholder and semi-mechanized processors. We applied the same principles to the range of values on the material mass balance of FFB and field data of all assumptions made ([Table A.1](#)).

Table 4

Composition of emissions from the combustion of biomass per tonne of fresh fruit bunch for the large-scale and small-scale processors.

Emissions	Large-scale Emission factor	Total boiler fuel (361.9 kg)	Small-scale Emission factor	Total boiler fuel (272.55 kg)
Parameter	(g/kg)	Emission to air (g)	g/kg)	Emission to air (g)
Methane	4.25	1538.44	4.97	1355.66
Dinitrogen oxide	5.67×10^{-2}	20.51	6.63×10^{-2}	18.08
Nitrogen oxides	1.23	444.59	1.51	411.475
Carbon monoxide	7.70	2784.82	9.46	2577.31
NMVOG*	4.05	1465.70	4.98	1356.48
Sulphur oxides	1.49×10^{-1}	53.74	1.82×10^{-1}	49.74
TSP**	2.30	830.56	2.82	768.67
PM10***	2.20	796.36	2.70	737.02
PM2.5***	2.16	781.70	2.65	723.46
Lead	3.65×10^{-4}	1.32×10^{-1}	4.48×10^{-4}	1.22×10^{-1}
Cadmium	1.76×10^{-4}	6.35×10^{-2}	2.16×10^{-4}	5.88×10^{-2}
Arsenic	2.57×10^{-6}	9.28×10^{-4}	3.15×10^{-6}	8.59×10^{-4}
Chromium	3.11×10^{-4}	1.12×10^{-1}	3.82×10^{-4}	1.04×10^{-1}
Copper	8.1×10^{-5}	2.93×10^{-2}	9.95×10^{-5}	2.71×10^{-2}
Selenium	6.75×10^{-6}	2.44×10^{-3}	8.30×10^{-6}	2.26×10^{-3}
Zinc	6.91×10^{-3}	2.58	8.49×10^{-3}	2.32
Benzo(a) pyrene	1.35×10^{-7}	4.89×10^{-5}	1.66×10^{-7}	4.52×10^{-5}
Benzo(b) fluoranthene	2.16×10^{-7}	7.82×10^{-5}	2.65×10^{-7}	7.23×10^{-5}
Benzo(k) fluoranthene	6.75×10^{-8}	2.44×10^{-5}	8.30×10^{-8}	2.26×10^{-5}

*Non-methane volatile organic compound, **TSP-Total suspended particulates, ***PM-Particulate matter.

Table 5

Emissions from open burning of biomass per tonne of fresh fruit bunch for the small-scale processors.

Emissions	Emission Factor (g/kg)	Total open burned fuel (391.15 kg) Emission to air (g)
Methane	6.5	2542.48
Dinitrogen oxide	1.5×10^{-1}	58.67
Nitrogen oxides	3.18	1243.86
Carbon monoxide	55.83	21837.90
NMVOG*	1.23	481.11
Sulphur oxides	1.1×10^{-1}	43.03
Total suspended particulates	4.64	1814.94
Particulate matter (PM10)	4.51	1764.09
Particulate matter (PM2.5)	4.19	1638.92
Lead	4.9×10^{-1}	191.66
Cadmium	1.0×10^{-1}	39.12
Arsenic	4.10×10^{-1}	160.37
Chromium	1.0×10^{-2}	3.91
Copper	2.0×10^{-1}	78.23
Selenium	7.0×10^{-2}	27.38
Zinc	17.53	6856.86
Benzo(a)pyrene	2.33	911.38
Benzo(b)fluoranthene	4.63	1811.02
Benzo(k)fluoranthene	5.68	2221.73

*Non-methane volatile organic compound

Table 6

Emissions to air from diesel combustion.

Emissions	Emissions Factor (g/MJ)	Large- scale (g)	Semi- mechanized (g)	Smallholder (g)
Carbon dioxide	74.1	1237.47	6321.47	2271.17
Methane	1.0×10^{-2}	1.67×10^{-1}	8.50×10^{-1}	3.10×10^{-1}
Dinitrogen oxide	6.1×10^{-4}	1.00×10^{-2}	5.00×10^{-2}	1.80×10^{-2}
Nitrogen oxides	3.1×10^{-1}	5.11	26.10	9.38
Carbon monoxide	9.3×10^{-2}	1.55	7.93	2.85
NMVOG*	2.0×10^{-2}	3.30×10^{-1}	1.71	6.10×10^{-1}
Sulphur oxides	9.4×10^{-2}	1.57	8.02	2.88
TSP**	2.1×10^{-2}	3.51×10^{-1}	1.79	6.40×10^{-1}
PM10***	2.1×10^{-2}	3.51×10^{-1}	1.79	6.40×10^{-1}
PM2.5***	1.8×10^{-2}	3.00×10^{-1}	1.54	5.50×10^{-1}
Lead	8.0×10^{-6}	1.34×10^{-4}	6.82×10^{-4}	2.45×10^{-4}
Cadmium	1.5×10^{-7}	2.51×10^{-6}	1.28×10^{-5}	4.60×10^{-6}
Mercury	1.0×10^{-7}	1.67×10^{-6}	8.53×10^{-6}	3.07×10^{-6}
Arsenic	5.0×10^{-7}	8.35×10^{-6}	4.27×10^{-5}	1.53×10^{-5}
Chromium	1.0×10^{-5}	1.67×10^{-4}	8.53×10^{-4}	3.07×10^{-4}
Copper	3.0×10^{-6}	5.01×10^{-5}	2.56×10^{-4}	9.20×10^{-5}
Nickel	1.3×10^{-4}	2.09×10^{-3}	1.07×10^{-2}	3.83×10^{-3}
Selenium	1.0×10^{-7}	1.67×10^{-6}	8.53×10^{-6}	3.07×10^{-6}
Zinc	1.8×10^{-5}	3.01×10^{-4}	1.54×10^{-3}	5.52×10^{-4}
Benzo(a)pyrene	1.9×10^{-9}	3.17×10^{-8}	1.62×10^{-7}	5.82×10^{-8}
Benzo(b) fluoranthene	1.5×10^{-8}	2.51×10^{-7}	1.28×10^{-6}	4.60×10^{-7}
Benzo(k) fluoranthene	1.7×10^{-9}	2.84×10^{-8}	1.45×10^{-7}	5.21×10^{-8}
Indeno(1,2,3- cd) pyrene	1.5×10^{-9}	2.51×10^{-8}	1.28×10^{-7}	4.60×10^{-8}

*Non-methane volatile organic compound, **TSP-Total suspended particulates, ***PM- Particulate matter

3. Results and discussion

3.1. Life cycle inventory

The emissions from biomass combustion during cooking fruits/steam generation and open incineration are presented in Tables 4 and 5, while the emissions from diesel combustion are shown in Table 6. Emissions from small-scale mills represent values emitted separately by the smallholder and semi-mechanized mills. The CO₂ from the combustion of the biomass is considered carbon neutral and not reported.

Figure 4 summarises each processors' contributions to gas emissions, including CH₄ and N₂O. The large-scale mill generated more total emissions than the smallholder and semi-mechanized mills. However, in terms of the overall management of biomass, smallholder and semi-mechanized mills generated more emissions than the large-scale mill, as shown in Figure 5. It should be noted that the PKS, MF and EFB disposed by burning are potentially available for the generation of electricity and can displace fossil fuels, for example, natural gas, diesel, and petrol, which are primary fuel sources for electricity generation in Nigeria. The CH₄ emission from EFB dumping was included in Figure 5, while the emissions from open burning of biomass in small-scale mills were added together. This supports the fact that more biomass

Fig. 4. Share of the emissions by percentage from biomass combustion (boiler) for a tonne of fresh fruit bunch in the mills. NMVOC-Non-methane volatile organic compound, TSP-Total suspended particulates, PM- Particulate matter.

Fig. 5. Share of emissions by percentage from all biomass combustion in the mills, including methane emissions from empty fruit bunch dumping in large-scale mills. NMVOC-Non-methane volatile organic compound, TSP-Total suspended particulates, PM- Particulate matter.

combustion will lead to more emissions but reinforces the influence of different environmental management practices. It is important to note that optimizing biomass quantity will contribute to lower emissions to the environment. Emissions from EFB combustion were avoided in large-scale mills, although it led to higher CH_4 emission from dumping, which can also be avoided through better management practices.

Table 6 is the summary of emissions from diesel combustion in the large-scale, semi-mechanized and smallholder systems. Diesel combustion is the primary source of fossil fuel use in oil palm industries. Evidently, more diesel consumption will lead to more emissions, as shown in Table 6. Semi-mechanized processors used more diesel power leading to more GHG and heavy metals emissions. Similarly, the smallholder processors contributed to more emissions than the large-scale processors. The small-scale mills' challenge is converting the biomass burned in the open into mechanical power to replace the diesel used in powering the processing machines. While steam produced in the semi-mechanized mill was estimated as 2966.17 MJ, using the same heat/power ratio above, the semi-mechanized mills can generate 156.94 MJ of electricity; the remaining 2809.23 MJ would be available as steam for the processes. This amount of electricity can replace the diesel used in the small-scale mills by 100%, except for the start-up of the boiler.

3.2. Elemental composition of POME

Table A.2 shows the composition of POME from semi-mechanized and smallholder mills. The parameters have been considered as

emissions to agricultural soil. The concentrations of metals in POME generated in the semi-mechanized mills are higher than in smallholder systems. POME disposal raises concern about the effects on aquatic organisms if it ends up in water bodies. Studies have been carried out on the impacts of POME disposal on soil properties. The phytotoxicity effect on seed germination and early plant growth using tomato seeds was reported by Nwoko et al. (2010). The study reported that phytotoxicity decreased when effluents were left to aerobically decompose for six days. Pre-treatment of POME is recommended, while suggestions are made to use POME for biogas/electricity generation (Gozan et al., 2018). The cost and environmental benefits of generating biogas from POME by these operators need to be further investigated. It offers an opportunity to reduce dependency on fossil fuel by replacing diesel in the industry. The operating capacities of these mills may pose a challenge and must be considered in any effort toward utilizing POME for biogas generation.

3.3. Emissions from aerobic digestion of POME

Table A.3 shows the emissions from POME pond during aerobic and anaerobic digestions in the large-scale mills. There are no reported emissions to air from POME in small-scale mills as stated above because the processors tend to dispose POME by pouring it away instead of storing it in the pond as obtained in large-scale mills. For 1 tonne of FFB in the large-scale mill, POME in the pond leads to about 7 kg of CH_4 emission compared to 5 kg from dumping EFB. The other emissions

Fig. 6. Greenhouse gas emissions from large-scale, semi-mechanized and smallholder mills per tonne of fresh fruit bunch.

include hydrogen sulphide, ammonia and N_2O .

Water consumption at the mills is related to POME production. In the small-scale mills, higher water consumption increases diesel use with the resulting emissions. Optimizing water use is an essential step in reducing emissions from diesel consumption. While the power generated using biomass is used in lifting water from water borehole in large-scale mills; higher water consumption will lead to more CH_4 emissions from POME. The other options for managing POME include deploying anaerobic digesters to produce biogas as reported by Nasution et al. (2018) and Andarani et al. (2018), and composting EFB with POME (Stichnothe & Schuchardt, 2011; Baharuddin et al., 2010). Any of these alternatives will improve the circular economy in the industry. Additionally, the generated biogas can displace fossil fuel in the industry, either in the mill or as vehicle fuel. Harsono et al. (2014) demonstrated that GHG emissions from biodiesel production could be reduced by 33% with POME anaerobic treatment.

3.4. Emissions from EFB dump

Table A.4 is the composition of EFB from large-scale mills. The large-scale mills usually dump EFB in heaps to decay; later, the manure would be spread over the plantation (Vijaya et al., 2008). As reported above, 50% of minerals in EFB would leach into the soil at the dumping site. However, it was assumed that the minerals were obtained from the soil during the growth stage of the palm trees. The higher anaerobic digestion taking place in the heaps leads to CH_4 emission. A higher stack of EFB will lead to more CH_4 emission. It is more convenient for the processors to pill the biomass to conserve space while the wet EFB decays over time. An effective means of reducing the CH_4 emission would be to spread the wet EFB over the plantation directly from the mill. However, it would come with an additional cost of diesel consumption. It is important to compare this alternative's environmental cost, especially considering that dried heaps of EFB are spread around the plantation after a year or more, which would also consume diesel. Stichnothe & Bessou (2017) reported the importance of management of the diverse biomass in the oil palm industry towards GHG emissions reduction, while Chanlongphitak et al. (2015) reported that EFB use for electricity generation is more environmentally friendly than fossil fuel in a life cycle assessment. Similarly, Norhasmillah et al. (2013) reported that EFB composting saved 89% of the time required for complete degradation of EFB compared to EFB mulching. Other options for managing EFB include composting EFB with or without POME and EFB as boiler fuel, as stated above.

Therefore, for a country like Nigeria, strict regulations are needed to enforce the operators in this section, especially large-scale processors, to reduce or completely stop avoidable emissions. In addition to creating a new business, it will go a long way in reducing the country's emissions at the local and global scale. Other countries with a similar situation can adopt the lessons.

3.5. Contributions of the mills to GHG emissions

Figure 6 represents the total contributions of the mills to greenhouse gas emissions. In the smallholder mills, we estimated about 47% and 73% more CO_2 and N_2O emissions than in the large-scale mills for 1 tonne of FFB, respectively. Also, the semi-mechanized mills produced 73% more N_2O than the large-scale mills. Similarly, in the semi-mechanized systems, 80% and 63% more CO_2 were estimated than in large-scale and smallholder mills, respectively. However, 71% more CH_4 emissions were produced in large-scale mills than in small-scale systems. It must be noted that when measured over a 100-year period, CH_4 is 25 times more potent than CO_2 , while N_2O is 300 times more potent than CO_2 . Life cycle assessment offers an opportunity to understand further these processors' contributions to the different impact categories. The analysis can be carried out using ReCiPe 2016 or Eco-indicator 99 methodology to link the emissions from LCI to environmental impact categories at midpoint or endpoint levels. Zulkifli et al. (2010) reported in a life cycle assessment of FFB production that N_2O emissions can be reduced when treated POME in the pond or EFB/POME compost is returned to the plantation to replace inorganic fertilizer.

As we have explained above, dumping of EFB and anaerobic digestion of POME in the large-scale mill contributed more to CH_4 and N_2O emissions (Vijaya et al., 2008). The level of technology at the small-scale mills ensures that POME generated can be easily managed by pouring away, which may not be the same when a single small-scale mill's capacity is increased. Similarly, the EFB, which is usually not sterilized in small-scale mills, can be combusted as fuel. Though, the small-scale production process leads to a higher quality of fuel (dry), the high free fatty acids in the produced crude palm oil is a challenge for these processors, especially if they must compete with the large-scale mills. However, there is a need to investigate the processes in the small-scale mills in terms of greenhouse gas emissions within the heaps of quartered FFB during the 2 to 4 days fermentation period and drying phase of the heaps of quartered empty fruit bunch. As demands for palm oil and palm kernel oil continue to grow, especially in the developing world, investment in the industry will be more attractive. New large-scale investors are more likely to reduce the share of small-scale processors in the industry. The economic gain may not benefit the environment compared to the displaced mills. It is crucial to consider the emissions hotspots identified in both the large scale and small-scale mills. This is particularly important because small-scale mills will likely suffer job shortages and financial struggle, leading to either being forced to close or refocus. Some plantation owners sometimes find it more economically beneficial to sell off the bunches instead of milling them in some places in Nigeria's oil palm belt. This leaves the mills idle and threatens the livelihood of workers dependent on fruit processing. It is worthy to note that the N_2O generated from the small-scale systems are from diesel and biomass combustion only. The open burning of biomass contributed to about 76% of N_2O emissions in the small-scale systems. Industry standard is needed in the small-scale sector; this will be helpful in GHG emissions monitoring and mitigation. For example, Schmidt & Rosa (2020) reported GHG emissions reduction in Roundtable on Sustainable Palm Oil certified palm oil compared to the uncertified. Figure 6 demonstrates that the technology for large-scale mills must be further advanced to reduce CH_4 emission, while the technology of small-scale mills should focus more on reducing CO_2 emission.

3.6. Sensitivity analysis

The results of the sensitivity analysis were compared with the baseline situations. The emissions to air from biomass combustion in the boiler of the large-scale, small-scale mills and the open burning of biomass for small-scale mills varied between $\pm 6\%$, $\pm 3\%$, and $\pm 5\%$ compared to the baseline results, respectively. When compared to the baseline results, the diesel use varied within -9 and +10%, -3 and +4%, and -3 and +7% for the large-scale, smallholder and semi-mechanized

Table A.1

Input data and their ranges used in the sensitivity analysis*.

	Smallholder			Semi-mechanized			Large-scale		
	BL**	Low	High	BL**	Low	High	BL**	Low	High
Diesel	31.67	30.65	32.90	85.31	82.88	90.99	16.7	15.1	18.3
Water	176.83	175.7	189.95	830.59	830.59	1006.46	1006.46	1000	1012.91
PKS	118.6	107.2	130	118.6	107.2	130	118.6	107.2	130
MF	243.3	234.6	252	243.3	234.6	252	243.3	234.6	252
EFB	301.8	292.3	311.3	301.8	292.3	311.3	301.8	292.3	311.3
Palm nut	179.5	167.5	191.5	179.5	167.5	191.5	179.5	167.5	191.5
POME	153.83	149.3	160.75	535.73	535.73	626.11	653.33	615	675.0

*Ohimain et al. (2013b), others were estimated from field and literature sources as reported in the text. BL**baseline input, PKS-palm kernel shell, MF-Mesocarp fibre, EFB-Empty fruit bunch, POME-palm oil mill effluent.

mills, respectively. The values are less sensitive (below $\pm 10\%$) to the changes in the diesel and biomass inputs for a 1 tonne of FFB except for the higher value of diesel in large-scale mills, which is moderately sensitive. The uncertainty in diesel use in large-scale mills may slightly affect the results. Similarly, the emissions from the EFB dumpsite varied within $\pm 3\%$ compared to the baseline situation. The emissions of hydrogen sulphide, ammonia, and dinitrogen oxide from the POME pond in the large-scale mills varied within -5 and $+3\%$, while that of methane was -1% and $+3\%$, compared to baseline emissions. Though a higher EFB heap would result in more anaerobic digestion, the variations are not significant. Overall, changes in the assumption do not lead to any considerable increase or decrease of the measured parameters.

3.7. Limitations/Constraints

Life cycle inventory analysis involves the compilation of inputs and outputs in the process and services within a system boundary. The accuracy relies significantly on data availability and quality. Uncertainty is inevitable in this study due to limited access to the national dataset for Nigeria, especially country-specific emission factors and output concerning FFB processing; data from Malaysia and Indonesia were used in some cases, which may not accurately represent the situation in Nigeria. The interventions related to construction, maintenance, use and disposal of all capital goods, including the power plant, buildings, and machinery, were not included. Some of these interventions are available in LCA software and databases. Additionally, there are variations in the construction of capital goods for small-scale processors in Nigeria. Therefore, more research is needed to establish an industry standard that could better judge interventions related to capitals goods by these processors.

4. Policy implication and conclusion

4.1. Policy implication

The study reveals critical hot spots of GHG emissions in Nigeria's oil palm industry, including CO₂ and N₂O from the smallholder and semi-mechanized processors and CH₄ from the large-scale processors. These findings will contribute to supporting policymaking to promote bioenergy use within and outside the industry as an essential strategy of mitigating climate change. Of particular interest is the small-scale processors who suffer economic losses due to a heavy reliance on diesel fuel. Effective bioenergy-based technology will increase the smallholder processor's productivity and reduce ecological effects, thus forming a more sustainable community and livelihoods. On the part of the large-scale mill, good management practices are needed for EFB and POME to reduce or stop the emissions associated with these waste streams, particularly CH₄. Finally, our research provides a reference for actions to other countries where the palm oil industry plays a vital role in the national economy and climate change mitigation.

Table A.2

Composition of palm oil mill effluent from semi-mechanized and smallholder processors.

Emissions	Ohimain et al. (2013b), g/kg	Semi-mechanized (535.73 kg), g	Ohimain et al. (2012), g/kg	Smallholder (153.83 kg), g
Dissolved Oxygen	4.69×10^{-3}	2.51	3.58×10^{-3}	5.51×10^{-1}
Chemical Oxygen Demand	1.81	967.71	1.95	300.14
Biological Oxygen Demand	3.83×10^{-1}	205.15	5.16×10^{-1}	79.41
Potassium	1.96×10^{-2}	10.52	1.81×10^{-2}	2.78
Nitrogen	1.29×10^{-2}	6.89	1.30×10^{-2}	2.01
Cadmium	3.00×10^{-5}	1.6×10^{-2}	1.20×10^{-5}	1.85×10^{-3}
Copper	2.44×10^{-3}	1.31	6.06×10^{-4}	9.32×10^{-2}
Iron	5.62×10^{-3}	3.01	4.90×10^{-3}	7.53×10^{-1}
Chromium	2.01×10^{-3}	1.08	1.08×10^{-3}	1.66×10^{-1}
Oil and grease	7.31×10^{-2}	39.15	6.43×10^{-2}	9.89

4.2. Conclusion

This paper presents life cycle inventory results of three types of processors in Nigeria's oil palm industry. The differentiation of processors is reflected in the level of technology they apply, which characterize their operational approach. The inputs and outputs (emissions and co-products) from each processor were estimated. The small-scale mills generate more GHG emissions, including CH₄, CO₂ and N₂O, resulting from a high diesel consumption. Specifically, the open burning of biomass residues in the small-scale mills emits a considerable amount of GHG emissions and causes air pollution. Moreover, more budget is spent on diesel consumption, while a potential source of bioenergy is disregarded. Our results highlight an urgent need for more research to develop affordable technologies to utilizing biomass-based energy by small-scale processors. The results identified GHG emissions hotspots enabling interventions/research on monitoring and/or mitigation. Furthermore, the life cycle impact assessment of the three processors is necessary to understand their impacts on environmental sustainability, which will assist in research, investment, and policy direction. There is a need for environmental techno-economic analysis or environmental life cycle cost analysis of new systems for the small-scale mills. Finally, the study opens an opportunity for a redesign of the small-scale oil palm industry to improve circularity and sustainability.

CRedit authorship contribution statement

Kelechi E. Anyaoha: Conceptualization, Methodology, Writing – original draft. **Lulu Zhang:** Supervision, Writing – review & editing.

Table A.3

Emissions to air from palm oil mill effluent pond of the Large-scale Processors.

Emissions to air	Applied	Unit
Methane	6.54	kg/t FFB
Hydrogen sulphide	5.63×10^{-2}	kg/t FFB
Ammonia	3.79×10^{-2}	kg/t FFB
Dinitrogen oxide	9.8×10^{-4}	kg/t FFB

Table A.4

Composition of empty fruit bunch.

Parameter	Anyaoha et al. (2020)* (mg/kg)	Baharuddin et al. (2010) (mg/kg)	Average (g/kg)	At 301.8 kg EFB (g)
Chromium	1.5		1.5×10^{-3}	4.53×10^{-1}
Copper	26	25.52	2.58×10^{-2}	7.77
Manganese	35	28.78	3.19×10^{-2}	9.92
Nickel	2.0	6.1	4.05×10^{-3}	1.22
Boron		26.97	2.70×10^{-2}	8.14
Zinc		33.0	3.3×10^{-2}	9.96
Phosphorus		8.0×10^{-2}	8.0×10^{-5}	2.41×10^{-2}
Potassium		2.01	2.01×10^{-3}	6.07×10^{-1}
Nitrogen		8.0×10^{-1}	8.0×10^{-4}	2.41×10^{-1}

*Unpublished data, which was part of Anyaoha et al. (2020)

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1

Table A.1, Table A.2, Table A.3, Table A.4

Reference

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