IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

International Journal of Sustainable Development and Planning
Vol. 18, No. 2, February, 2023, pp. 447-455
Journal homepage: http://iieta.org/journals/ijsdp

Review on Carbon Footprint of the Palm Oil Industry: Insights into Recent Developments

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https://doi.org/10.18280/ijsdp.180213

Received: 21 December 2022
Accepted: 3 January 2023

Keywords:
palm oil industry, palm oil milling, carbon footprint, GHG emissions, sustainability

ABSTRACT

A typical palm oil mill is estimated to produce greenhouse gas emissions of 637–1,131 kg CO_2 eq/t crude palm oil. Huge efforts are being made to reduce the carbon footprint of palm oil mills. However, the data from such research works have not been consolidated. This paper is a critical review of the most recent developments in the palm oil milling process and unit operations that leads to greenhouse gas emissions, specifically focusing on the development of palm oil mills today. In addition, the paper explored the importance of energy self-sufficiency of palm oil mills. To do so, the author compared this configuration with a mill that requires an external power supply and estimated that a self-sufficient palm oil mill could potentially reduce emissions by 457 kg CO_2 eq/t crude palm oil. Methods with the greatest positive effect on the carbon footprint have been identified for further investigation.

1. INTRODUCTION

Palm oil is an edible vegetable oil that is derived from the fruit of the oil palm tree. It is an agricultural commodity produced on a large scale and is consumed and traded globally. In order to satisfy the high demand for vegetable oils, global palm oil production increased from 24 million tons (t) in 2000–2001 to approximately 73 million t in 2020–2021 [1]. The main palm-oil-producing countries are Indonesia and Malaysia, which produced 46.5 and 19.8 million t palm oil, respectively, in 2020–21, equivalent to 85% of the world's total production [1]. The worldwide demand for palm oil is expected to hit 156 million t by 2050 [2]; it is mainly driven by rapidly growing populations and an increase in per-capita consumption [2, 3]. Such an increase in the demand for palm oil can be attributed to the fact that it is relatively cheap and versatile, both in its edible and non-edible industrial applications. Palm oil can be fractionated into a liquid called olein and a solid called stearin. Olein is widely used as cooking and frying oil, whereas stearin finds its applications in solid fat formulations and food processing. Palm oil and palm kernel oil are important raw materials for the oleochemical industry.

However, the production of crude palm oil (CPO) is frequently criticized for the emission of greenhouse gases (GHG) and other sustainability-related issues. The main GHGs in Earth's atmosphere are water vapour, carbon dioxide, methane, nitrous oxide and ozone [4]. To tackle global climate change, Indonesia and Malaysia, the world's two largest palm oil producers, have made tremendous efforts to adopt sustainable practices in palm oil production and improve their carbon footprint. According to Pandey et al. [5], carbon footprint is defined as the "quantity of GHGs expressed in terms of carbon dioxide equivalent (CO_2 eq), emitted into the atmosphere by an individual, organization, process, product or event from within a specified boundary".

A few research works have focused on improving the sustainability of palm oil mills through environmental assessments of palm oil production, applications of renewable energy, and utilization of the generated biomass [6, 7]. Life cycle assessments have also been performed on CPO production [8-10]. However, a thorough scientific review of the carbon footprints of palm oil mills with different configurations is lacking. Thus, the environmental improvements made by the industry over the years have not yet been documented.

In the current paper, GHG emissions at different unit operations of a typical palm oil mill are discussed. Further, the latest initiatives taken to reduce the carbon footprint in palm oil mills are examined. The unique configuration and the importance of self-sufficient palm oil mills are also discussed. To achieve these goals, a collection and analysis of academic papers were conducted. Paper search was primarily done using several large academic databases and search engines, including, but not limited to, Scopus, Google Scholar, PubMed and MDPI. The research was conducted manually using phrases such as "palm oil," "carbon footprint," "life cycle assessment" and "greenhouse gas." For each of these keywords, the results were examined considering the factors found in the literature review.

2. PALM OIL MILL OPERATION

Although palm oil mills' design is based on the concepts developed in the early 1950s [11, 12], there have been significant improvements in all aspects of milling over time. The typical palm oil milling process is best described in the form of activities at different stations (Figure 1). Fresh fruit bunches (FFBs) from plantations are transported to a palm oil mill. Milling operations include reception, sterilization, threshing, digestion, pressing, clarification, purification and kernel recovery. The primary products are CPO and palm kernels. The generated biomass comprises empty fruit bunches, pressed mesocarp fibres, palm kernel shells and decanter solids, whereas the liquid by-product is palm oil mill effluent (POME), which is the combination of many waste sources such as sterilizer condensate, the heavy phase from clarification and wastewater from wet separation. A palm oil mill also has a boiler station and a power plant that drive steam turbines to generate power and facilitate various processes [13-15].

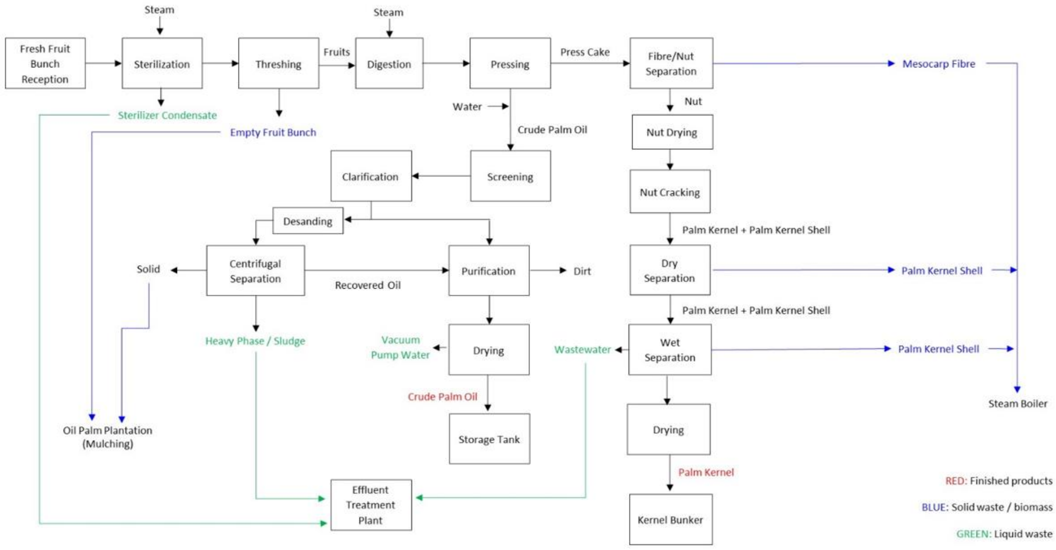

Figure 1. Typical palm oil milling process flow

2.1 Reception and sterilization

FFBs delivered to the palm oil mill are inspected and graded for ripeness and other characteristics before being loaded onto ramp hoppers and cages. These cages are moved into a horizontal sterilizer and a pressure vessel. FFBs are then sterilized at 143°C and 300 kPa for approximately 90 min. This sterilization process helps deactivate the lipase enzymes which are responsible for the formation of free fatty acids and loosen the individual fruits from bunches for easier separation in subsequent processing. In addition, it preconditions the nuts to reduce palm kernel breakage during both pressing and nut-cracking processes. The sterilizer condensate generated during this process is a primary source of POME [16, 17]. The sterilization process has been improved by many new processes and technologies. Various new sterilizers have been introduced, including cage-less continuous horizontal, vertical, tilting, oblique, spherical and multi-door system horizontal kinetic sterilizers. The labour-intensive capstan and bollard system has been replaced by partially and fully automated cage movement systems [3]. These improvements have not only increased process efficiency and safety but also reduced the overall dependence on labour and vehicles and, thus, fossil fuel consumption.

2.2 Threshing

A thresher is a horizontal rotating drum. Sterilized fruit bunches are loaded at one end and are then lifted and dropped repeatedly as they make their way through a rotating drum, during which the palm fruits are separated from the bunch stalks. Detached palm fruits pass through bar screens in the drum and are conveyed to a digester, while bunch stalks (i.e. empty fruit bunches) are returned to the plantation as mulch and manure or are used as a solid fuel for the steam boiler.

2.3 Digestion and pressing

The digestion and pressing stations are the core of the palm oil mill and are where palm oil is extracted from the fruits. Fruitlets discharged from the thresher are conveyed to vertical cylindrical digesters, where they are steam-heated and mashed by stirring arms to loosen the mesocarp from the nuts and to break up oil-bearing cells to facilitate better oil release. Digested mash is then fed into a continuous screw press to extract or squeeze out the rich oil-containing liquor, which leaves behind a press cake that consists of pressed mesocarp fibres and nuts. The digestion and pressing stations have also seen continuous improvements. The screw press design has been improved to allow palm fruits to undergo either single- or double-screw pressing. The double-screw press system enables maximal oil extraction with minimal nut breakage. The screw press capacity has been increased from 3–4 to 25–30 tons FFB/h to reduce the number of units in operation. The most recent development is the use of enzymatic technology to improve oil extraction [18].

2.4 Clarification and purification

The Press liquor extracted during pressing comprises a mixture of palm oil, water and solid or fibrous materials. It is diluted with hot water and then screened through a vibrating screen to remove coarse contaminants. Subsequently, it is clarified in a vertical settling or clarifier tank, where gravity separation takes place. In the lighter phase, oil is skimmed off from the top and purified through a high-speed centrifuge to remove any traces of impurities before being sent to a vacuum dryer to remove moisture. Finally, CPO is transferred into a storage tank before it is dispatched to refineries for further processing. The underflow or sludge is the heavier phase and is discharged from the bottom of the clarifier tank, following which it is fed into the desander and then a centrifugal separator such as a decanter or sludge separator for remnant oil recovery. The remaining water and fibrous debris or generated heavy phase is discharged as POME [17]. Although the press liquor is commonly diluted with hot water, some oil mills use a new oil recovery system without dilution that can significantly reduce the amount of liquid by-product generated.

2.5 Kernel recovery

The other product from the pressing station is the press cake. A pneumatic separation system is used to separate nuts and pressed mesocarp fibres. The nuts are cracked to produce kernels and shells, which are separated by a dry separation process using a multi-stage winnowing system followed by a claybath and/or hydrocyclone (wet separation). The wastewater generated from wet separation is another source of POME [17]. Palm kernels are then dried and stored before being dispatched to kernel-crushing plants, whereas palm kernel shells and pressed mesocarp fibres are used as fuel for steam and electricity generation. Palm oil mills are energy self-sufficient because of the voluminous biomass available.

2.6 Boiler station

The boiler station produces steam to drive a steam turbine and generate power to facilitate various processes such as sterilization, digestion and clarification. Steam generation has advanced from less-efficient and labour-intensive small-capacity fire-tube boilers to automated water-tube boilers, including a "walking floor" boiler fuel storage system, moving grates for fuel combustion and an ash removal system [3]. This has reduced the dependence on loaders and manual labour. Biogas is now being captured from POME for combustion in the boiler for additional energy.

2.7 Effluent treatment plant

The processing of FFBs for CPO and palm kernels results in a liquid by-product in the form of POME, which is generated from the sterilizer, claybath or hydrocyclone, and the sludge separator or decanter. While POME is non-toxic, it is the primary cause of environmental pollution when untreated because of its high acidity, chemical oxygen demand and biochemical oxygen demand. The most commonly used effluent treatment system is the ponding system with anaerobic and aerobic digestion. New tertiary systems have been developed to treat effluent more sustainably and meet stringent regulations. Many palm oil mills are now investing in new technologies to harvest biogas for fuel and reuse other biomass materials to create an extra revenue stream.

3. RESULTS

3.1 GHG emissions

GHGs exist in gaseous form in the atmosphere. They absorb and emit radiant energy within the infrared radiation range, contributing to global warming and climate change [19]. Previous research works have reported that the two major GHG emissions sources associated with palm oil milling operations are methane emission from POME treatment in open ponds and fossil fuel consumption [20]. Boiler fuel-gas stacks are another source of GHG emissions. Table 1 summarizes the GHG emissions attributed to palm oil milling operation.

Table 1. GHG emissions from a palm oil milling operation

GHG Emissions (kg CO_2 eq/t CPO production)			**Ref.**
POME Digestion	Boiler Emissions	Fossil Fuel Consumption	
758[a, b]	-	-	[21]
744	-	11.1	[22]
637	-	14.1	[23]
1,094	-	-	[24]
885	-	11.1	[25]
792	170.2	-	[26]
965–1,131[b]	41.28–67.68	9.1–21.3[c]	[8, 27]
-	-	5.0[c]	[28]

Note: (a) Average CPO production of 199.5 kg/t FFB [29]; (b) Methane has a Global Warming Potential of 25 [4]; (c) Emission factor of 2.70 kg CO_2 eq/L diesel consumption [30]

3.1.1 POME Digestion

Among the three major GHG emission sources, POME digestion in an open ponding system is the dominant one [31, 32]. It is the most common POME treatment and has been adopted by over 85% of palm oil mills [33]. A ponding system comprises acidification, anaerobic and facultative (i.e. aerobic) ponds. Biogas mainly comprises methane, carbon dioxide, trace components of hydrogen sulphide and other gases [34] that are emitted from POME treatment ponds during the anaerobic process. As a GHG, methane is 25 times as potent as carbon dioxide [35].

Previous studies have reported that a mill producing 1 t CPO without biogas capture emits 637–1094 kg CO_2 eq from POME [21-24]. Vijaya et al. [8] reported that the 12 oil mills selected for their study produced GHG emissions worth 965–1131 kg/t CPO due to POME digestion. These studies support the values of 885 and 792 kg CO_2 eq/t CPO reported by Kulim [25] and Sime Darby Plantation [26], respectively. The small variations in the results were attributed to differences in the ratio of POME generated to 1 t FFBs processed, which may be caused by seasonal trends for the crops, the quantity of water used for crude palm oil dilution, wet separation process in kernel recovery station, such as claybath and/or hydrocyclone, and cleaning of the oil mill [27, 36]. On top of that, the quantity of POME generated depends also on the crude palm oil clarification and purification technology and effluent recycling initiative. For example, by using emerging technology, not only that extra water dilution is not needed, but also the POME generated is recycled and mixed with shredded empty fruit bunches at a purpose-built composting plant for organic fertiliser production. This system can reprocess all POME generated by an oil mill into fertiliser, thus significantly reducing effluent generation.

3.1.2 Boiler emission

The emission of pollutants from the steam boiler has a significant environmental impact. The combustion of pressed mesocarp fibres, palm kernel shells, empty fruit bunch fibres, or a combination of the above in the boiler's furnace emits pollutants such as carbon monoxide, nitrogen oxide, sulphur dioxide and particulate matter. Vijaya et al. [27] reported that boiler stacks emit 41.28-67.68 kg CO_2 eq/t CPO. Sime Darby

Plantation [26] reported that their boiler emitted 170.2 kg CO_2 eq/t CPO. This variation may be attributed to the different approaches used for emission prevention and particulate collection such as cyclone dust collectors, electrostatic precipitators and bag-house filter systems. In addition, the difference in GHG emissions from the flue gas stack could be explained by the type and mixture of the biomass used as boiler fuel. Generally, pressed mesocarp fibres have higher moisture content and ash content compared to the palm shell. Hence, when more pressed mesocarp fibres are burned, more particulate is expected to be generated.

3.1.3 Fossil fuel consumption

Palm oil mills can be energy self-sufficient if they use biomass for cogeneration. However, electricity is still needed for offices, lighting, the housing complex and other facilities within the mill and estate compound when the mill is not in operation. Electricity is supplied by a diesel generator set if the mill is not connected to the electrical grid. Diesel is also needed for vehicles used by the mill. The diesel consumption of tractors and loaders varies depending on the operating hours and level of automation employed in the milling process. Kaewmai et al. [22] and Bessou et al. [23] found stated that fossil fuel consumption for production, transportation and combustion resulted in GHG emissions of 11.1 and 14.3 kg CO_2 eq/t CPO, respectively. Vijaya et al. [8] selected five oil mills that were not connected to the electrical grid and found GHG emissions worth 9.1–21.3 kg CO_2 eq/t CPO, with an average of 14.9 kg CO_2 eq/t CPO, as presented in Table 1. These findings align with the value of 11.1 kg CO_2 eq/t CPO reported by Kulim [25]. However, Subramaniam et al. [28] reported a lower emission value. They found that oil mills had a fuel consumption of 0.37 L diesel/t FFB, which translates to 5.0 kg CO_2 eq/t CPO based on the Malaysian average of 199.5 kg CPO/t FFB in 2017–2020 [29] and an emission factor of 2.70 kg CO_2 eq/L diesel [30].

Since the quantity of diesel used to power appliances and lights in buildings is greater than that required to operate heavy vehicles, the variations in the results could be explained by the duration of boiler operation. Assuming two oil mills have similar processing hours, the one with longer boiler operation hours would need less diesel fuel. This is possible if the mill is either equipped with a "walking floor" boiler fuel storage system, which enables a continuous feeding of biomass to the steam boiler or channelling biogas captured from POME for combustion in the boiler, even during non-processing hours.

3.2 Carbon footprint reduction

Almost all sectors of the global economy are major contributors to GHG emissions, including energy, transport, forestry and land use, agriculture, industrial processes and waste generation [37]. Developments are being made to reduce palm oil mills' carbon footprint. These initiatives are summarized in Table 2.

Table 2. Developments for reducing the carbon footprint

Initiatives / Developments	**Benefits**	**Remarks / Findings**	**Ref.**
Biogas capture from POME	GHG emissions drop 85%	GHG emissions decrease from 546.9 and 896.5 kg CO_2 eq/t CPO to 82.0 and 134.5 kg CO_2 eq/t CPO, respectively.	[27]
	GHG emissions drop by 90%	GHG emissions decrease from 650 to 70 kg CO_2 eq/t CPO.	[38]
	Generate carbon offsets of 4,264–5,117 kg CO_2 eq	Biogas is exported to the electrical grid for electricity generation.	[3]
	See "Biomass as Sold Fuel"	Palm kernel shells can be used as an alternative to fossil fuels.	
Biodiesel Production from Palm Sludge Oil	Reduce 84.1%–85.3% GHG emission compared with fossil fuel	Palm sludge oil from POME is converted into biodiesel and used in vehicle engines.	Table 3
Enzyme-assisted Oil Extraction Process	Reduce 9% GHG emissions per ton CPO	Not much detail is found. This could be attributed to the lower methane emissions from open ponds.[a]	[39, 40]
Biomass Utilization as Solid Fuel	Generate carbon credit of 87.4 kg CO_2 eq/t CPO	Palm kernel shells are used as an alternative to coal and other fossil fuels.	[41]

Note: (a) Based on the author's experience and observations as a chemical engineer and palm oil mill engineer

3.2.1 Biogas capture from POME

Biogas plants can be installed in palm oil mills to not only generate renewable energy but also prevent methane emissions. POME generated during palm oil milling operation is retained for some time before being discharged. The biogas produced by POME degradation can then be utilized for power generation or is flared to ensure that methane is not released into the atmosphere. One ton of CPO yields approximately 85.55 m3 of biogas comprising 65% methane and 35% CO_2 with other trace gases [8]. Vijaya et al. [27] found that biogas capture reduces GHG emissions due to POME by 85% from 546.9 to 82.0 and 896.5 to 134.5 kg CO_2 eq/t CPO, respectively. Gan and Cai [38] found similar results, with a 90% reduction in GHG emissions from 650 to 70 kg CO_2 eq/t CPO. The biogas captured from POME can be utilized in various ways. Biogas can be used as renewable energy to produce heat or electricity or a combination of both [42-44]. Hong [3] reported that a mill with a processing capacity of 90 t FFB/h could produce 1,000–1,200 m3 raw biogas/h. The biogas can be exported to the electrical grid to produce approximately 6,500–7,800 kWh worth of electricity based on energy content of 6.5 kWh/m3 [45]. For Malaysia, this translates into carbon offsets or carbon credits amounting to 4,264–5,117 kg CO_2 eq or 198.4–238.1 kg CO_2 eq/t CPO based on an emission factor of 0.656 kg CO_2 eq/kWh worth of electricity [46] and average production of 199.5 kg CPO/t FFB in 2017–2020 [29]. When biogas is used in steam boilers, it offsets the use of palm kernel shells. This enables biomass to be used as an alternative to fossil fuels, which can also generate carbon offsets or carbon credits. This is how the palm oil industry could contribute to emission climate neutrality, that is, through biogas capture from POME.

3.2.2 Biodiesel production from palm sludge oil

Instead of being left in the effluent treatment pond, palm sludge oil could be an attractive natural source for biodiesel production; not only is it a cheap raw material, but utilizing it can help address global sustainability challenges [3]. As an alternative to petrodiesel, biodiesel offers considerable benefits regarding GHG emissions. The carbon footprint of biodiesel production using palm sludge oil as feedstock can be evaluated by calculating the GHG emissions reduction compared to fossil fuels. Because palm sludge oil is a residue from milling, it has zero life cycle GHG emissions up to the point of collection [47]. Hence, the system boundary for this assessment includes esterification and transesterification processes and transportation of the biodiesel to Europe for (co-generated) electricity production. The esterification and transesterification processes include the conversion of glycerides and free fatty acids into biodiesel [39, 48]. The scope of transportation includes the transportation of the biodiesel from the biodiesel plant to the port and shipment to the EU [24]. Depending on the fossil fuel comparators, biodiesel produced from palm sludge oil has a GHG emission reduction potential of 84.1–85.3% (see Table 3), which is above the 70% threshold specified in the Renewable Energy Directive (RED) II [49]. Although palm sludge oil-based biodiesel can significantly reduce greenhouse gas emissions as compared to fossil-based diesel, the usage of palm sludge oil-based biodiesel in the region has yet to change significantly.

Table 3. Palm sludge oil biodiesel production: Estimated GHG emissions

	Value	**Unit**	**Ref.**
Output			
Palm sludge oil biodiesel	1,000.00	kg biodiesel/1,111 kg palm sludge oil	
Input			
Utility			
Steam	388.89	kg/t biodiesel	
	151.67	g CO_2 eq/t biodiesel	[24]
Electricity	33.33	kWh/t biodiesel	
	30,322.67	g CO_2 eq/t biodiesel	[24]
Nitrogen	2.78	kg/t biodiesel	
	156.67	g CO_2 eq/t biodiesel	[50]
Chemical			
Methanol	133.33	kg/t biodiesel	
	257,638.67	g CO_2 eq/t biodiesel	[50]
Liquid enzyme	13,333.33	g CO_2 eq/t biodiesel	
Potassium hydroxide	16.67	kg/t biodiesel	
	6,985.00	g CO_2 eq/t biodiesel	[50]
Hydrochloric acid	16.67	kg/t biodiesel	
	17,685.00	g CO_2 eq/t biodiesel	[50]
Sodium hydroxide	5.56	kg/t biodiesel	
	2,942.78	g CO_2 eq/t biodiesel	[50]
Citric acid	0.56	kg/t biodiesel	
	535.06	g CO_2 eq/t biodiesel	[51]
Total GHG emissions of biodiesel	329,750.84	g CO_2 eq/t biodiesel	
	8.91	g CO_2 eq/MJ biodiesel	
Total GHG emissions of biodiesel, including transport to EU	13.86	g CO_2 eq/MJ biodiesel	[24]
GHG emissions reduction versus fossil comparator I	84.1%	Fossil comparator with 87.3 g CO_2 eq/MJ biodiesel	[52]
GHG emissions reduction versus fossil comparator II	85.3%	Fossil comparator with 94 g CO_2 eq/MJ biodiesel	[49]

Unless otherwise specified, the information is based on the author’s experience and observation.

3.2.3 Enzyme-assisted oil extraction process

Enzymatic technology can make the palm oil industry greener and more efficient by breaking down the cellulose and hemicellulose matrixes in the oil-bearing cell walls [18, 53, 54]. Enzymes are applied either to the palm fruits before digestion or to the diluted crude oil after pressing [55-57]. While this is an emerging technology in the field of palm oil milling, a full-scale mill operation with an enzymatic palm oil extraction process recorded a 4% increase in the oil yield, a 9% reduction in GHG emissions and a 4% reduction in land use per ton of CPO produced [39, 40]. Although it is unclear where the improvement comes from, a possible factor may be the reduced methane emissions from open ponds.

3.2.4 Process biomass utilization as solid fuels

Biomass is generated in huge quantities in the palm oil industry, including in the form of empty fruit bunches, pressed mesocarp fibres and palm kernel shells. In recent years, empty fruit bunch fibres and pressed mesocarp fibres have been used instead of palm kernel shells as solid fuels for the steam boiler [58-60]. This allows palm kernel shells to be sold for external use as a renewable energy resource [41]. This is also consistent with the finding that it is possible to produce pellet solid fuels from biomass stalk and pulp [61].

Palm kernel shells are classified as a renewable energy source that complies with the energy regulations of developed countries such as Japan, Korea, and in Europe [3]. In Malaysia, biomass boilers are becoming popular because of their attractive design, as well as low maintenance and cost. Palm kernel shells are the first choice of biomass material, followed by wood chips and sawdust pellets [3, 62]. This explains the high demand for palm kernel shells in recent years. Palm kernel shells, if used to replace coal and other fossil fuels for energy generation, can generate carbon offsets or carbon credits of 87.4 kg CO_2 eq/t CPO [41]. So, upgrading palm biomass into a renewable energy source would not only promote better utilisation of agricultural waste but also help achieve our societal goals on climate.

4. DISCUSSION

4.1 GHG avoidance

Palm oil mills are energy self-sufficient because of the voluminous biomass available. However, not many studies have investigated the importance of this unique configuration. Hence, no proper evidence has been documented on how the use of biomass for steam and power generation curbs GHG emissions. Palm oil mills typically have three electricity sources: the electrical grid, steam turbines fuelled by biomass and a diesel-powered generator set [8]. Under normal operating conditions, the steam turbines are used to generate electricity. The electrical grid or diesel generator set is only used during the daily start-up of mill operation or non-processing hours. Pressed mesocarp fibres, empty fruit bunch fibres and palm kernel shells are biomass generated by the milling operation. They can be used separately or in combination as solid fuel feedstock for the steam turbines. The generated steam and electricity are primarily used on-site, as well as in the employees' housing complex.

When calculating GHG emissions, researchers often disregard the unique self-sufficiency of palm oil mills. This model is not commonly seen in other industries. For example, soybean oil is the second most produced and consumed vegetable oil worldwide, and its production is generally supplied by electricity and steam from the electrical grid and natural gas, respectively [63-65]. Therefore, disregarding the recycling of biomass as solid fuel feedstock unfairly distorts the carbon balance sheet of palm oil mills.

Table 4 indicates that a palm oil mill using biomass as a solid fuel feedstock reduces GHG emissions by 456.83 kg CO_2 eq/t CPO compared to a mill that only uses electricity and steam generated from fossil fuels. These values were determined based on the average amounts of power and steam required to produce 1 t CPO in Malaysia. As a wider implication, the self-sufficient model of palm oil mills avoided GHG emissions of approximately 33.22 million t in 2019–20, which is equivalent to 0.1% of global energy-related GHG emissions, which was reported to be around 33 Gt in 2019 [66].

Table 4. Palm oil milling operation: Estimated GHG emissions when fossil fuel is used

Descriptions	Value	Unit	Ref.
Input			
Power	102.61	kWh/t CPO	[6], [8]
Steam	2.64	t/t CPO	[6], [8]
Impact			
Power			
Total GHG emissions due to diesel used	67.31	kg CO_2 eq/t CPO	[46]
Steam			
Energy required to produce steam needed	6943.23	MJ/t CPO	
(a) Heat required to heat up water from 30°C to 100°C	772.09	MJ/t CPO	
(b) Heat required to convert water at 100 °C into steam at 100°C	5,968.48	MJ/t CPO	
(c) Heat required to convert steam at 100 °C into steam at 145°C	212.65	MJ/t CPO	
Total GHG emissions due to natural gas consumption	389.52	kg CO_2 eq/t CPO	[67]
Total GHG emissions due to fossil fuel consumption	456.83	kg CO_2 eq/t CPO	

5. CONCLUSION

This review aimed to present a consolidated view of the most recent developments in the palm oil milling process and unit operations that leads to greenhouse gas emissions, focusing on the development of palm oil mills today. Based on the review, a mill that does not utilize biogas or methane capture has been estimated to emit 637–1,131 kg CO_2 eq/t CPO. The industry has nonetheless established a few initiatives to reduce palm oil mills' carbon footprint, which include capturing biogas from POME, converting palm sludge oil into biodiesel, deploying an enzyme-assisted oil extraction process and using biomass for energy generation as an alternative to fossil fuels.

In addition, the paper explored the importance of energy self-sufficiency in palm oil mills. To do so, the author compared this configuration with a mill that requires an external power supply and estimated that a self-sufficient palm oil mill could potentially reduce emissions by 457 kg CO_2 eq/t crude palm oil.

Based on the standard calculation scheme proposed by the Renewable Energy Directive and using data published in various reliable sources, the author tentatively concluded that biodiesel produced from palm sludge oil has a GHG emission reduction potential of 84.1–85.3% as compared to fossil-based diesel. Since this has a great positive effect on the carbon footprint, a proper life cycle assessment should be conducted to evaluate the actual environmental impact of the palm sludge oil-based biodiesel production process.

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