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Gate-to-gate life cycle assessment of crude palm oil in palm mills in West Aceh-Indonesia

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ABSTRACT

Mass flows of palm oil processes require energy to convert input into output. The energy requirements of a continuous palm oil processing system can provide a complete overview of the process of producing palm oil, palm kernel oil, and the generation of solid wastes and liquid waste (POME). Analysis of energy potential in the biomass involved in a 60-ton-per-hour fresh fruit bunches (FFB) processing revealed a potential for solid waste at the stripping station (EFB 28%), depericarper (fiber 17.61%), and hydrocyclone (shell 32.02%), and liquid waste potential at the sterilization station (49.68%), hydrocyclone (18.31%), sludge in the sludge tank (0.38%), sludge separator tank (31.55%), and oil purifier (0.08%). The value of the liquid waste potential has a significant and direct impact on the environment, forming greenhouse gas emissions (global warming potential), such as CO_2, NO_x, NH_4, or CO_2-eq, human health, resource quality, climate change, and resources from each palm oil processing station. The greatest potential CO_2-eq value is yielded by processes in the station that produce palm oil, including stripping, digester, and pressing. The possible values, such as global warming potential (GWP CO_2eq), is 4.81×10^3, 4.56×10^3, and 9.49×10^3, respectively. For cradle-to-gate LCA, the significant environmental impacts are acidification (253.1 kg-SO_2eq), eutrophication (93,719 kg-PO_4eq), water footprint (10,387 m^3), and energy consumption (969,920 MJ). The influence of cradle-to-gate life cycle management has a direct impact on the use of input and output energy in a process, especially in the process of processing FFB to produce palm oil, palm kernels, and fiber waste, EFB, as well as liquid waste which can be used as organic fertilizer for sustainable palm oil plantations.

Keywords: palm oil mill, CPO, LCA, potential global warming, cradle-to-gate.

INTRODUCTION

The energy balance in the production of crude palm oil (CPO) from fresh fruit bunches (FFB) requires careful management of the input and output energy within a closed system (Bantacut & Pasaribu, 2015; (Bantacut & Novitasari, 2016). This includes managing input-output inventories (Vijaya *et al.* 2008; Subramaniam et al., 2010a; Zulkifli et al., 2010), and the processing of FFB at palm oil mills (Stichnothe & Schuchardt, 2010; Er et al., 2011; Abdullah & Sulaiman, 2013; Agustiar et al., 2020), alongside the use of electricity and water in these processes (Faisal and Mahidin, 2013; Kospa et al. 2017). A mill with a capacity of 60 tons per hour requires approximately twice the electrical energy of a 30-ton FFB mill, ranging from 20 to 25 MW (Mahlia et al., 2001; Bantacut & Pasaribu, 2015; Hidayat et al., 2017), This highlights the significant energy demands of the CPO production process (Mahlia et al., 2001; Yusoff, 2006; Hayashi, 2007).

Under existing conditions, palm oil production consumes large amounts of energy and water, resulting in the generation of both solid and liquid waste (Bantacut et al., 2014; Kramanandita *et al.*, 2014; Bantacut & Pasaribu 2015; Susanto et al., 2017), The waste typically consists of 2–15% fiber, 5–7% shell, and 20–23% empty fruit bunches (EFB) based on the processing capacity of FFB (Haryanti et al., 2014; Rahayu et al., 2018; Agustiar et al., 2020). The fiber-to-shell ratio is around

70:30, with the shell being a viable fuel for direct combustion in boilers to produce high-temperature steam (Ahmad et al., 2016; Izah et al., 2016; Harahap et al., 2019).

The processing requires 20 hours per day, with machine efficiency capacity at 80% (Mahlia et al., 2001; Hidayat et al., 2017), producing crude palm oil through digestion, pressing, and oil purification, within a closed system (cradle-to-gate) (Espino et al., 2019). Each process directly impacts environmental emissions in the surrounding area (Scarlat and Dallemand, 2011; Zhuo et al., 2020), with indirect emissions affecting human health (Scarlat and Dallemand, 2011; Rega and Ferranti, 2019). Solid and liquid waste from the process impacts the soil and produces unpleasant odors, especially during prolonged rainfall (Kar and Tekeli, 2008; Rupani & Singh, 2010; Pandia et al., 2020). This can also influence the palm oil industry processes in a region and impact the surrounding community environment near palm oil mills.

The byproducts of oil palm processing, such as EFB, fiber, palm oil mill effluent (POME), and shell, have significant potential as alternative energy sources (renewable energy) (Hosseini & Wahid, 2014; Wu et al., 2017), these materials can replace steam in palm oil processing, serve as substitutes for biodiesel (Sugiyono, 2008; Cappelli et al., 2015; Hamzah et al., 2019), and be utilized in power generation (Shuit et al., 2009; Kurka and Blackwood, 2013). FFB yield CPO at rates of 10-30% (Wicke et al., 2008), with solid waste generation ranging from 30–70%, and liquid waste at 60-79% (Faisal & Mahidin, 2013; Ohimain & Izah, 2014), and the contribution of the composition of solid waste includes empty fruit bunches (20–23%), fiber (12–15%), and shell (5–7%) (Nasution et al., 2014).

The energy potential of waste generated from palm oil processing continues to be evaluated in this research. Numerous competent studies have highlighted the potential of solid waste (Husain et al., 2003; Shuit et al., 2009; Foo and Hameed, 2010; Ohimain and Izah, 2014), and liquid waste (Gobi & Vadivelu, 2013; Pandia et al., 2020). The environmental impacts assessed through life cycle assessment (LCA) processes, considering both inputs and outputs, demonstrate the environmental effects at each stage of the inventory process as energy sources (Subramaniam et al., 2010b; Gunarso et al., 2013). The extensive use of electricity and water contributes to the emissions that affect air, water, and soil, potentially leading to environmental impacts measured in terms of CO_2 equivalent (kg-CO_2eq), including CO_2, NO_x, and CH_4 emissions, as well as human health impacts, environmental quality, and resource quality. (Jolliet et al., 2003; McManus & Taylor, 2015; Al-Hamamre et al., 2017; Rega & Ferranti, 2019), Additionally, the conversion of liquid waste into energy can help reduce greenhouse gas emissions (CH_4) (Kar & Tekeli, 2008; Kaygusuz, 2009).

This research cannot precisely predict the amount of energy each station generates in the palm oil processing chain. The process is conducted based on the mass balance or equilibrium balance of each station, which determines the quantity of waste generated and the magnitude of environmental impacts resulting from electricity consumption throughout the process, as illustrated in Figure 2.

METHOD

Analysis of the balance in CPO production process

The mass balance process involves calculating the balance between input and output in the CPO production, considering inventory inputs, outputs, and waste (Kramanandita et al., 2014; Bantacut & Romli, 2020). The mass balance analysis does not account for chemical or physical properties of the palm fruit at each processing station, but instead focuses on the stages leading to CPO production. The energy balance method and mass balance were used alongside the Simapro Software Version 9 Pre Consultant to analyze the environmental impacts or emissions from each station during the process, employing methods such as IMPACT 2002+, Recipe 2016 (Jolliet et al., 2003; Steubing et al., 2016). These methods are designed to assess the environmental impacts on human health, ecosystem quality, global warming potential, and resources (Jolliet et al., 2003; Sadhukhan et al., 2019; Singh et al., 2013), utilizing Eco-Indicator 99 (Goedkoop and Spriensma, 2001), and CML (Finnveden et al., 2009; Hischier et al., 2010). These factors are evaluated in the life cycle impact assessment (LCIA) inventory throughout the operation of each station. The functional unit (FU) for palm oil is defined as 1 ton of CPO, which will be converted into CO_2 equivalents (Reijnders & Huijbregts, 2008; Davis et al., 2009; Van Rikxoort et al., 2014).

The mass and energy balance calculations are based on the previously established equations (Bantacut & Pasaribu, 2015). The analysis reveals that the composition of waste generated during the processing of fresh fruit bunches (FFB) includes various waste types, such as solids (empty fruit bunches, fibers, and shells), liquids (water and sludge), and other by-products. These wastes are produced at different stations, including stripping, depericarping, hydrocycloning, sterilization, sludge tanks, sludge separator tanks, oil purifiers, and hydrocyclones (Tables 1 and 2). The mass balance equation is as follows:

$$Input\ mass\ (Min) = Output\ mass\ (Mout) \quad (1)$$

The mass balance of palm oil processing is calculated at various stations, including sterilization, threshing/stripping, digestion, pressing, continuous settling tanks (CST), sludge tanks (ST), and sludge separator tanks (SST). This process operates cyclically at CST, ST, and SST, where the materials are continuously recycled back into the CST, and then into the oil purifier, vacuum dryer, and oil storage tank (Agustiar et al., 2020; Kramanandita et al., 2014).

Life cycle assessment analysis from cradle to gate

According to ISO 14040, life cycle assessment (LCA) is a technique used to assess the environmental impacts associated with a product (Menoufi, 2011; Ling-Chin et al., 2016). LCA compiles and inventories the inputs and outputs related to the production of a product (Vijaya et al., 2008; Chauhan et al., 2011; Ling-Chin et al., 2016;) as well as evaluates the potential environmental impacts (Phang & Lau, 2017; Sadhukhan et al., 2019). It interprets the results of the analysis at each stage of the study (Klöpffer, 2006; Klöpffer & Grahl, 2014; Ling-Chin et al., 2016; Darojat et al., 2019). The LCA cycle begins with raw material extraction, production processes, transportation, operation, and recycling activities (Vijaya et al., 2008; Desinta Sawitri Giandadewi and Pertiwi Andarani, 2017; Yusuf et al., 2019), and in this study, a gate-to-gate boundary system was applied, which is from material coming in up to a product out of factory (Subramaniam et al., 2010).

Within this cycle, LCA provides environmental impact information for the activities that produce a product (Chauhan et al., 2011). This phase starts by calculating the input and output throughout the entire life cycle of production process, including material and energy use (input) and the products generated (output). This study is a part cradle to cradle LCA that offers insight into the environmental impact of a produced from the production activities (Finnveden et al., 2009). Data processing for environmental impact assessment consists of three elements: characterization, normalization, and weighting (Yusoff & Hansen, 2007; Finnveden et al., 2009). These assessments identify the most significant environmental contributions.

FFB conversion into CPO

The system boundary defines the identification of inputs, outputs, and environmental impacts within a palm oil mill, particularly focusing on the process of converting FFB into CPO. The CPO processing is presented in Figure 1.

RESULTS AND DISCUSSION

Mass and energy balance in the crude palm oil (CPO) process

The mass and energy balance calculations for the palm oil production process are illustrated in Figure 2.

Sterilization

The palm fruit, transported to the sterilizer via a fresh fruit bunch (FFB) conveyor, undergoes sterilization for 1 hour. The separated mixture is collected in an oil recovery tank for reclaiming the oil, while the condensate is pumped to the waste treatment station. A total of 60 tons of FFB are loaded into the sterilizer from the transport lorry before being processed into oil. The sterilization temperature ranges from 125 °C to 135 °C, requiring 82-90 minutes (Bantacut & Pasaribu 2015). The steam requirement accounts for 27.26%, while exhaust steam represents 3.65%, producing 85% sterilized fruit from the original FFB. This output consists of 1.8% ripe fruit and 23.16% condensate, which further includes 0.68% oil, 3.69% solids, and 95.63% water condensate. The electrical energy required for the sterilization process is 39,912.12 MJ per hour, equivalent to 11,086.47 kWh. The balance of the CPO processing can be observed in the illustration provided in Figure 2.

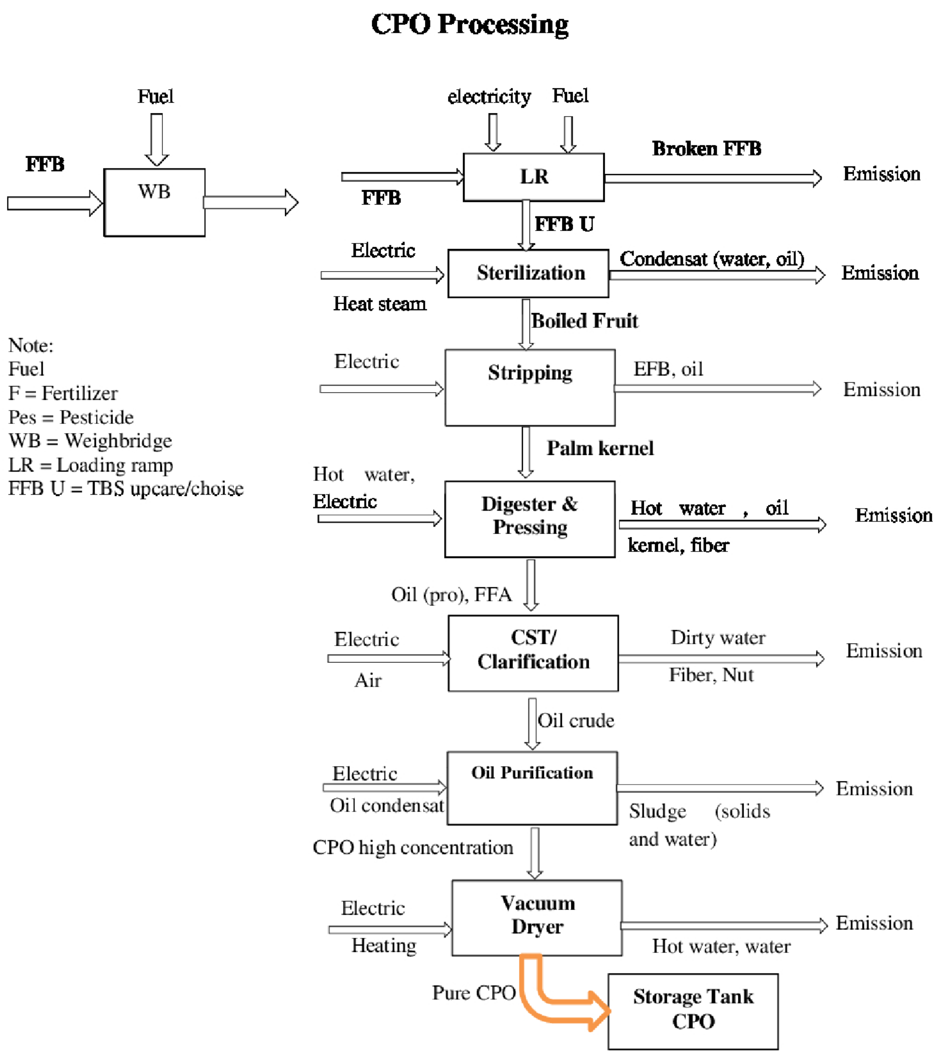

Figure 1. CPO production process flow section

Stripping

Sterilized FFB, which account for 85% of the total input, are fed into the stripping drum to separate the fruit from the bunches, operating at a speed of 33.95 rpm. This process yields 32% EFB, consisting of 3.36 kg/hr of oil, 16,801 kg/hr of EFB, and 117,607 kg/hr of loose fruits, with palm fruits weighing 35,438 kg/hr. The composition of loose fruits includes 17,718.73 kg/hr of fruit and 561.59 kg/hr of water. The energy requirement for the stripping process is 617,889 MJ/hr or 171,636 kWh, while energy released to the atmosphere is 85,645.02 MJ/hr or 21,960.26 kWh.

Digester

The loose fruit from the stripping process enters the digester, which separates the pulp from the nut. This process involves mashing the fruit with rotating blades while heating to a temperature of 90-95 °C (Kramanandita et al., 2014). The feed for the digester comprises 98.5% fruit and 1.5% water, with a steam requirement of 6.67% of the total feed. The process results in 106.67% mass, including 92.6% loose fruit and 7.94% water. The electrical energy required for this mashing process is 1,921.54 kWh or 7,494.006 MJ/hr.

Pressing

The mashed fruit, which consists of 92.60% fruit and 7.94% water, is transferred to the pressing machine, where hot water (approximately 20% of the total mass) is added. The pressing process produces about 66% crude oil, which includes 46% oil, 42.8% water, 7% solids, and 4.2% free fatty acid (FFA). It also generates 54.5% fiber, 1.5% water, and 44% nut. The electrical energy

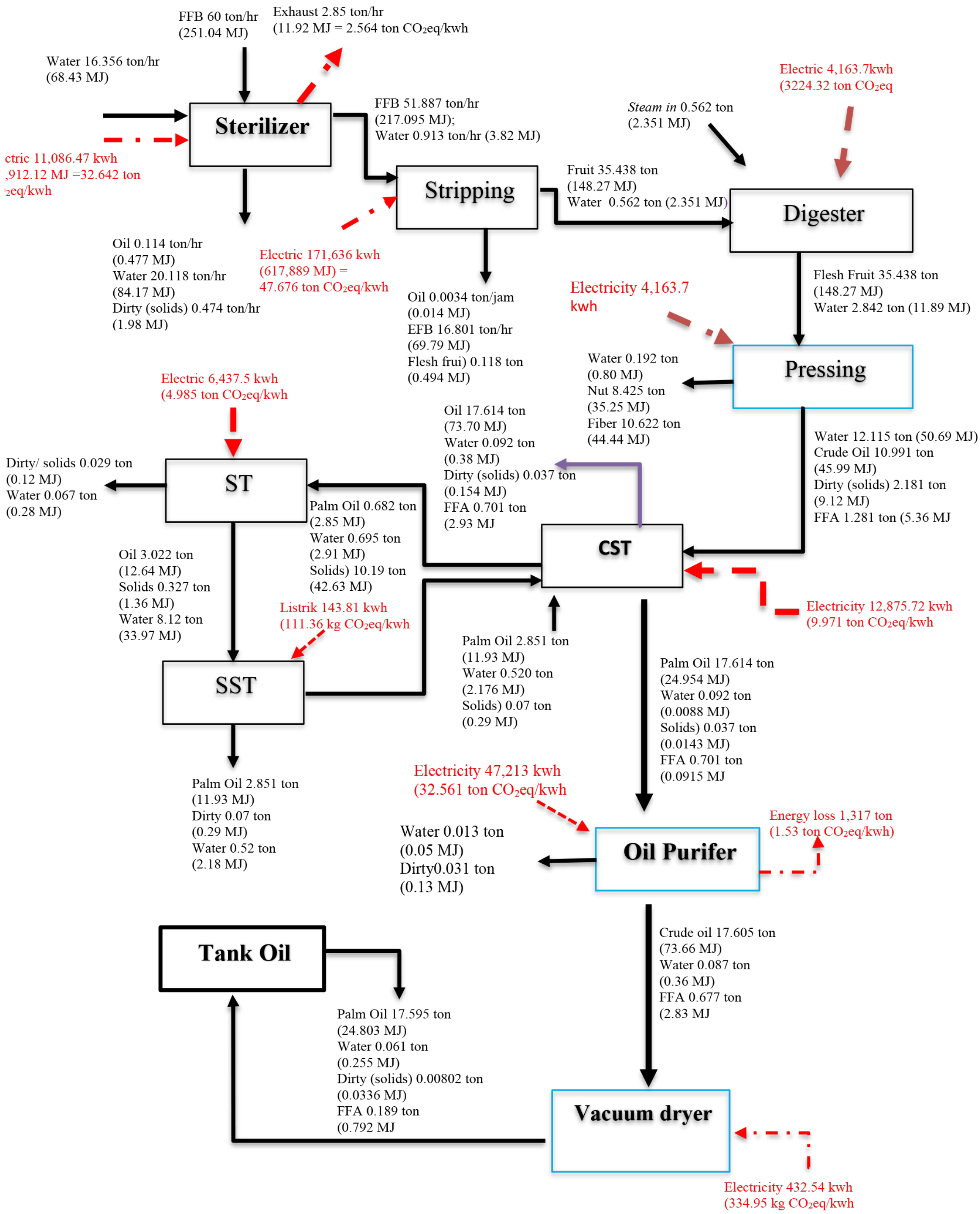

Figure 2. Detailed energy balance of palm oil mill (Kramandanita, *et al*., 2014)

used in the pressing process is 1,921.54 kWh or 7,494.01 MJ/hr.

Continuous settling tank (CST)

The crude oil from pressing, consisting of oil (46%), water (42.8%), solids (7%), and FFA (4.2%), is conveyed to the continuous settling tank (CST) for initial clarification. In this tank, separation occurs by gravity, with two main components:

- the sludge tank,
- the sludge separator tank.

The clarified mixture returning to CST consists of 84.5% oil, 13.25% water, and 2.25% solids. The process requires low electrical energy (heat loss) of 219.81 kWh or 857,259 MJ/hr. The initial crude oil clarification starts with 18,944.3 kg/hr (58.74%), including 1,117.71 kg/hr (5.9%) oil, 1,138.55 kg/hr (7.5%) water, and 16,688 kg/hr (88.09%) solids. After treatment in the sludge tank and separator tank, the clarified oil returns to CST.

Sludge tank

The oil-bearing sludge from CST is pumped to the sludge tank, where oil is separated from the sludge using gravity. The sludge composition includes approximately 75.33% water and 24.67% solids, which is directed to the effluent pond as POME. The crude oil mixture from the sludge tank comprises 27.5% oil, 70.5% water, and 2% solids, and is then transferred to the sludge separator tank. The energy requirement for this station is 2,971.08 kWh or 11,587.21 MJ/hr (Kramanandita et al., 2014). The process recycles oil from the sludge tank back to the CST, with an estimated oil recovery of 95.50%.

Sludge separator tank

Oil from the sludge tank is further processed in the sludge separator at 90 °C to separate oil from sludge. The composition of the separated oil includes 29.22% oil, 70.78% water and solids, which is returned to CST. The clarified oil is composed of 84.50% oil, 2.25% solids, and 13.25% water, while the co-product sludge is sent to the effluent pond containing 95.05% oil, 0.55% solids, 0.45% water, and 3.50% FFA.

Oil purifier tank

The oil from the oil tank is sent to the oil purifier to remove impurities. The purified oil consists of 95.50% oil, 0.45% water, 3.50% FFA, and 0.55% solids. The waste from the oil purifier, comprising 2.98% solids and 97.02% water, is discharged to the effluent pond (POME). The energy required for the oil purification process is 23,606.3 MJ/hr or 6,052 kWh/hr.

Vacuum dryer

Oil from the oil purifier, containing 96.50% oil, 0.45% water, 2.92% FFA, and 0.13% solids, is fed into the vacuum dryer to reduce the water content from 0.45% to 0.002%. The resulting oil is stored as CPO. The process consumes 163,419.04 MJ/hr or 41,902.32 kWh of steam energy and 778.51 MJ/hr or 199.62 kWh of electrical energy. The vacuum dryer separates water from the oil, reducing water content by approximately 0.98%.

Oil tank

The final CPO stored in the oil tank contains oil (96.80%), water (0.002%), FFA (3.07%), and solids (0.13%). Over time, water evaporates, solids settle, and the oil retains its free fatty acid content.

Potential energy from palm oil waste

The processing of FFB to produce palm oil also generates potential energy from the waste produced at various stages, such as stripping, depericarper, and hydrocyclone. These processes yield energy-rich by-products such as EFB, fiber, and shells. Table 1 highlights the dominant waste products: 16,801 kg/h of EFB, 10,556.37 kg/h of fiber, and 3,653.47 kg/h of shells. In terms of percentage, EFB accounts for 28%, fiber 17.61%, and shells 6.06%. Previous research (Hosseini *et al.* 2013; Ohimain & Izah 2014) has demonstrated the potential of converting these solid wastes into biohydrogen, biogas (Ahmad et al., 2016), and bioethanol (Kaygusuz 2009; Acaroĝlu & Aydoĝan 2012).

The liquid waste produced, consisting of water and sludge, originates from the sterilization station, sludge tank, sludge separator tank, oil purifier, and hydrocyclone. Each station generates liquid waste with varying compositions of solids and water. Liquid waste containing water primarily is produced at the sterilization and hydro cyclone stations, while sludge is generated at the

Table 1. Solid waste potential

Station	Type of waste	Composition	Volume (kg·hr^{-1})
Striping	EFB	Oil 0,03%, EFB 99,28%, and loose fruits 0,7%, at 90 °C	16,801
Depericarper	Fiber	Fiber 96%, nut 4%, at 40 °C	10,556.37
Hidrocyclone	Shell	Shell 99%, kernel 1%	3,653.47
Total			31,010.835

Note: Bantacut & Pasaribu, 2015.

sludge tank, sludge separator tank, and oil purifier stations. The amount of water produced totals 28,337.73 kg/h, while the sludge composition accounts for 13,340.097 kg/h. The overall volume of liquid waste produced is 69.46%, equivalent to 41,677.83 kg/h. The potential development of this liquid waste could serve as an alternative energy source (Gobi and Vadivelu 2013; Ohimain and Izah 2014), such as biohydrogen (Kramanandita et al., 2014; Ahmad et al., 2016), and water recovery (Kelly-Yong *et al.* 2007; Bantacut and Novitasari 2016), as shown in Table 2.

Global warming potential (GWP) in palm oil processing

GWP, based on a worldwide metric (Recipe Global GWP100), indicates the global warming potential caused by emissions over a 100-year timeframe. Greenhouse gas (GHG) emissions in this study are considered a significant source of GWP (Steubing et al., 2016; Darojat et al., 2019). The value of greenhouse gas emissions is expressed in potential global warming, measured in kilograms of CO_2 equivalent (kg-CO_2eq.). These values are periodically reported by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2006; Siangjaeo et al., 2011). GHG100, as expressed in kg CO_2eq., primarily consists of CO_2. Other gases, such as CH_4 and N_2O, also have substantial GWP equivalent values, with CH_4 having a value of 25 kg-CO_2eq. and N_2O having a value of 298 kg-CO_2eq (Kelly-Yong et al., 2007; Hosseini and Wahid 2015). However, CO_2 remains the primary contributor to global warming, as it is the main product of hydrocarbon-oxygen reactions.

The GWP of greenhouse gases during the FFB processing to produce CPO presents a significant risk of contributing to global warming (Hischier *et al.* 2010; Gerbens-Leenes 2013; Dincer and Bicer 2018). The process emits greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), expressed as kg-CO_2eq., which impacts environmental sustainability (McManus & Taylor 2015; Al-Hamamre *et al.* 2017). The potential effects of these emissions include global warming, climate change, eutrophication, acidification, and human health risks (Jolliet *et al.* 2003; Rega and Ferranti 2019). Each station in the FFB processing has the potential to generate CO_2eq. emissions from the various stages of production.

The CO_2eq. emissions from each station in the palm oil processing are calculated per unit process, with a functional unit (FU) of 1 ton. The LCA impact category shows the CO_2eq. emissions per hour for each processing station. The highest emissions occur at the oil purifier station (19×10^3 kg-CO_2eq.), the continuous settling tank (15.6×10^3 kg-CO_2eq.), and the vacuum dryer (19.1×10^3 kg-CO_2eq.). These elevated emissions are likely due to the significant electricity consumption from diesel or gasoline fuel, which results in high CO_2eq. Emissions at each hotspot in the palm oil processing stations (Schmidt, 2010). The potential impacts extend to human health, climate change, eutrophication, acidification, water footprint, and energy consumption (Table 3). The impact category can be evaluated using the IMPACT 2002+ method, which integrates various approaches, such as IMPACT 2002 (Jolliet et al., 2003; Hischier et al., 2010), Eco-Indicator 99 (Goedkoop and Spriensma 2001), CML (Jolliet et al. 2003; Wardenaar et al., 2012), and the IPCC method (http://www.impactmodeling.org). These impacts are observed in the process of producing palm oil and palm kernel oil from FFB (Jolliet et al., 2003).

Global warming potential emission values

The impact assessment (impact category) presented in Table 3 illustrates GWP in units of kg CO_2-eq., highlighting the most significant impact at each processing station. The impact values indicate hotspots occurring at the vacuum dryer (19.1

Table 2. Liquid waste potential

Station	Type of waste	Composition	Volume (kg·hr^{-1})
Sterilization	water	Water (97.16%), oil (0.55%), solids (2.29%), at 90 °C	20,706.05
Sludge tank	sludge	Water (70%), solids (30%), at 90 °C	157.24
Sludge separator tank	sludge	Oil (0.90%), water (96%), solids (3,10%)	13,150,92
Oil purifier	sludge	Water (70%), solids (30%)	31.94
Hydro cyclone	water	Water (100%), at 30 °C	7,631.68
Total			41,677.83

Note: Bantacut & Pasaribu 2015.

Table 3. Impact catagory LCA

No	Impact category	Unit	Sterilization	Thresher	Digester	Pressing	CST	Oil purifier	Vacuum dryer	CPO tank	Total
1	GWP, Global (Recipe, 2016) (H)	kg-CO_2eq	1,290	4,810	4,560	9,490	15,600	19,000	19,100	19,400	93,250
2	Acidification (Recipe, 2016) (H)	kg-SO_2eq	2.53	14.5	13.8	28.8	47.3	58.9	58.4	59.7	283.93
3	Eutrophication ((Recipe, 2016) (H))	kg-PO_4eq	0.379	5.86	5.61	11.7	19	24.2	26.7	24.3	117.75
4	Water footprint (AWARE, V 1.03)	m^3	61.1	590	566	1,180	2,100	2,610	2,670	2,710	12,487
5	Energy consumption (HHV (CED, 1.11)	MJ	7,220	49,600	47,300	98,800	161,000	202,000	201,000	203,000	969,920

Note: H is version hierarchist, AWARE is available water remaining, HHV is high heating value, CED is cumulative energy demand (Subramaniam *et al.* 2010; Steubing *et al.* 2016).

× 10^3 kg-CO_2eq.), oil purifier (19 × 10^3 kg-CO_2eq.), and continuous settling tank (CST) (15.6 × 10^3 kg-CO_2eq.). The greenhouse gas emissions, including CO_2, CH_4, and N_2O, have been converted into CO_2 equivalent emissions based on their GWP, as outlined in the assessment reports released by the Intergovernmental panel on climate change (Dal Ferro et al., 2016; Fiorese et al., 2013; Darojat et al., 2019). The impact category values show significant variations, ranging from very low to high, depending on the processing stage in palm oil production (CPO), as depicted in Figure 3.

Acidification emission values

Acidification refers to the decrease in soil and water pH due to the formation of H^+ ions (Espino et al., 2019). The potential acidification value (acidification potential) shows the highest impact in CPO storage (storage tank) with 59.7 kg-SO_4eq, followed by the oil purifier at 58.9 kg-SO_4eq, and the vacuum dryer at 58.4 kg-SO_4eq. The major contributors to SO_2 and NO_x emissions in palm oil processing are primarily associated with electricity use in the vacuum dryer stage. Clean palm oil composition is reported at 96.50%, solids at 0.13%, water at 0.45%, and free fatty acids (FFA) at 2.95%. These findings are supported by previous studies (Siddiquee & Rohani, 2011; Faisal & Mahidin, 2013; Kramanandita et al., 2014). The acidification emission values for processing 60 tons per hour of FFB show significant acidification potential (AP) in the vacuum dryer and CPO tank (Figure 4). These processes also exhibit the highest emission potential for SO_2 and NO_x, specifically in the palm oil processing

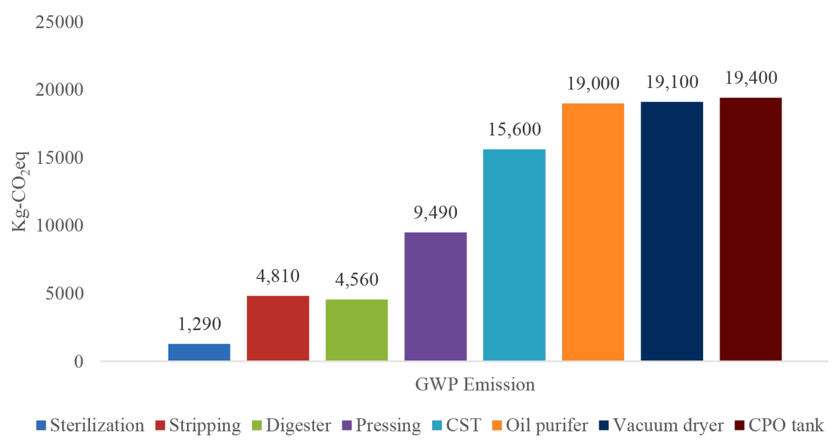

Figure 3. Emission value potential with GWP (kg-CO_2eq)

industry, with electricity usage contributing to water content of 0.47%, FFA content of 3.68%, and pure palm oil content of 95.68% before vacuum drying (Bessou & Pardon, 2016; Darojat et al., 2019). Electricity consumption in processing 60 tons per hour primarily relies on the energy from palm kernel shells (PKS). The AP classification factor is based on the contributions of SO_2, NO_x, HCl, NH_3, and HF, expressed in SO_2 equivalents (Darojat et al., 2019).

Eutrophication emission values

The potential eutrophication impact due to emissions is expressed in kg-PO_4^{3-}eq. From the processing of 60 tons per hour of palm oil, the eutrophication emission values (PO_4^{3-}) are significant, with the highest contributions recorded as follows: 24.3 kg-PO_4^{3-}eq from the CPO tank, 24.2 kg-PO_4^{3-}eq from the oil purifier, and 19 kg-PO_4^{3-}eq from the continuous settling tank (CST) (Darojat et al., 2019). Numerous studies suggest that eutrophication values are often referred to as nitrate equivalents, as nitrate is the most dominant component in the emission composition.

In the palm oil processing industry, the generation of PO_4^{3-}, NO_3^-, and NO_x contributes to eutrophication. PO_4^{3-} and NO_3^- are primarily produced from wastewater treatment, while NO_x is emitted due to the use of diesel-powered electricity. The eutrophication values for palm oil processing can be observed in Figure 5.

Water footprint emission values

The water footprint is a comprehensive indicator of both direct and indirect water usage in production and consumption processes (Zhuo et al., 2020). In the palm oil processing industry, the water footprint measures the water used per 1 ton of fresh fruit bunches (FFB/m³) to produce CPO, palm kernel oil (PKO), EFB, shell, fiber, and POME (Ahmad et al., 2016; Garcia-Nunez et al., 2016; Hambali & Rivai, 2017).

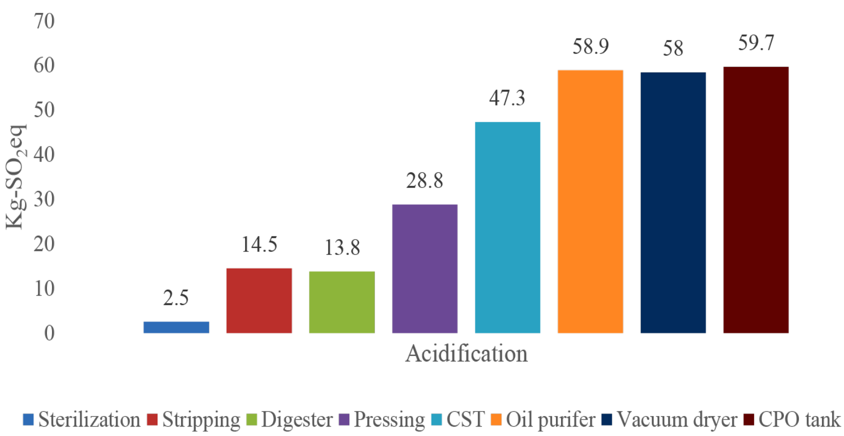

Figure 4. Emission value potential to acidification (kg-SO_2eq)

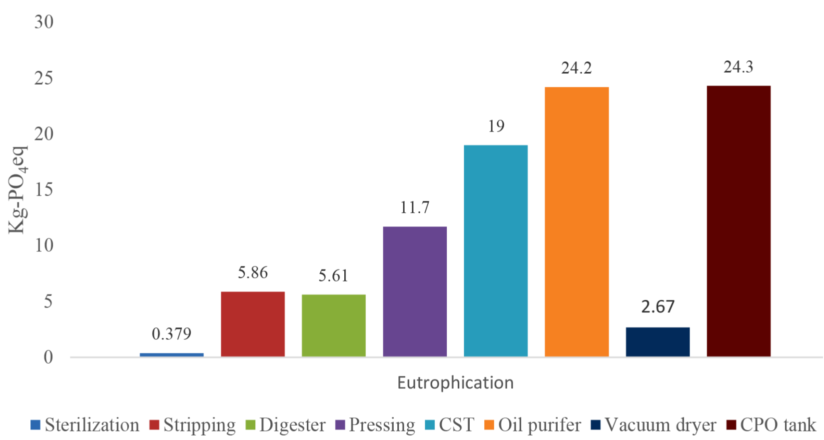

Figure 5. Emission value potential to eutrophication (kg-PO_4eq)

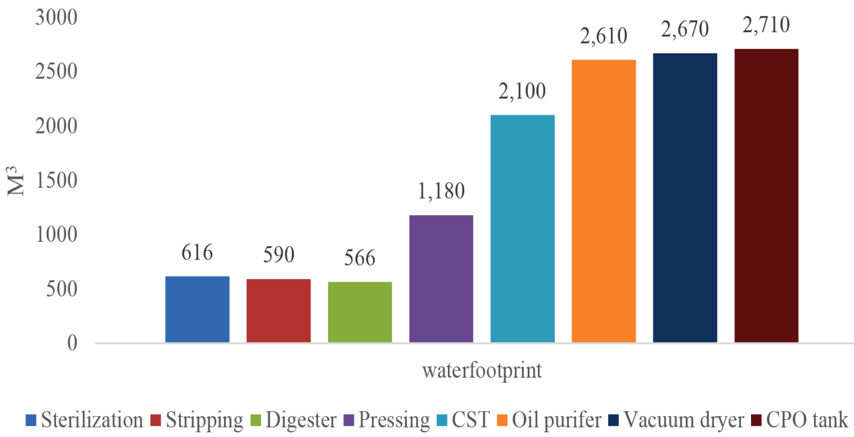

Figure 6. Emission value potential to water footprint (M^3)

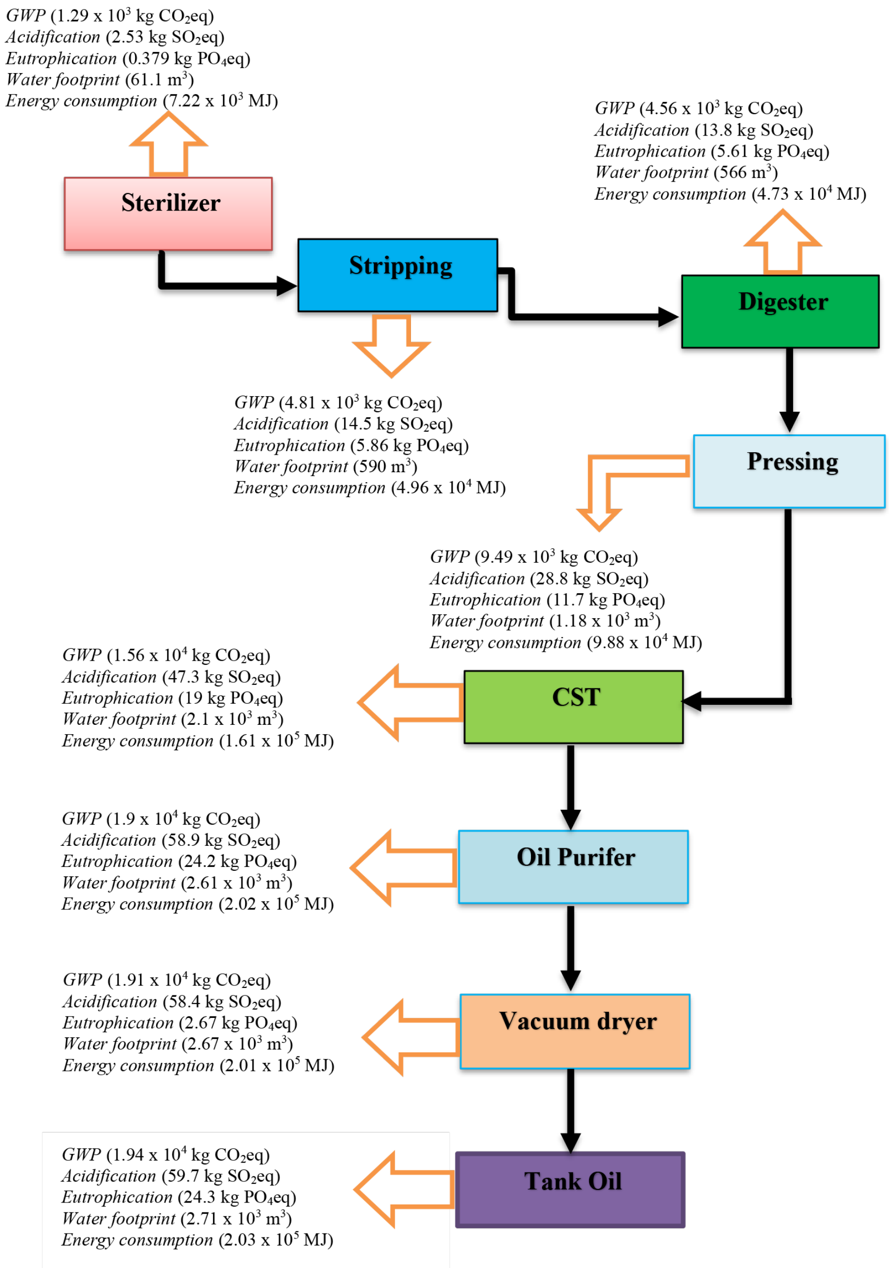

Figure 7. Model LCA emission GWP (kg CO_2-eq) at processing CPO

In the processing of 60 tons of FFB per hour, water is used at various stages, following the LCA method. The vacuum dryer consumes 5.38 m³ per ton of FFB, the CPO tank consumes 5.42 m³ per ton, and the oil purifier consumes 3.9 m³ per ton. The sterilization process uses the least amount of water, at 1.11 m³/ton of FFB. Research by (Boulay et al., 2013) shows that water use in LCA serves as a key indicator of both product and co-product sustainability, providing a methodology for assessing water resource usage and forming an LCA framework for water footprint evaluation (Noviantari et al., 2015; Hoekstra, 2016).

The total water consumption in processing 60 tons per hour of FFB amounts to 11,903 m³/ton FFB (Figure 6). Energy consumption across various stages, including sterilization, stripping, digestion, pressing, CST, oil purifier, vacuum dryer, and CPO tank, is distributed as follows: 0.52%, 0.05%, 4.75%, 9.91%, 17.64%, 21.93%, 22.43%, and 22.77%, respectively. The majority of energy consumption occurs during oil purification, vacuum drying, and CPO storage, totaling 67.13% of the energy used in the palm oil production process (Zulkifli et al. 2010; Bantacut & Pasaribu 2015; Wu et al. 2017).

Carbon emission potential (CO_2-eq) in LCA from gate to gate

The potential of carbon emissions or greenhouse gases (GWP CO_2eq) presents a significant environmental concern when generated continuously from palm oil processing for CPO production (Stichnothe & Schuchardt 2010; Steubing et al. 2016). Each stage of the processing, starting from sterilization, through stripping, digestion, pressing, CST (continuous settling tank), oil purification, vacuum drying to storage has a measurable impact based on the input materials used. LCA analysis on these inputs shows that the emission potentials such as GWP, acidification, eutrophication, water footprint, and energy consumption significantly contribute to carbon emissions (CO_2eq) at each stage of the process (Zulkifli et al., 2010; Subramaniam et al., 2010b; Darojat et al., 2019).

The values for each process vary, influenced by the mass balance during the processing of FFB into CPO. The inputs and outputs of each stage have different impacts on the LCA category, which in turn results in different emission values across each process (Subramaniam et al., 2010b; Gunarso et al., 2013).

Significant CO_2-eq emission values are generated in all stages of processing, with the CST, oil purifier, vacuum dryer, and CPO tank contributing the highest emission impacts (kg-CO_2eq) compared to other stages. Table 3 presents the emission values generated by the LCA gate-to-gate process, including units for GWP (kg-CO_2eq), acidification (kg-SO_2eq), eutrophication (kg-PO_4eq), water footprint (m³), and energy consumption (MJ) (Klöpffer, 2006; Stichnothe & Scuchardt, 2011; Klöpffer & Grahl, 2014; Darojat et al., 2019). The total impact category values for the 60 tons/hour FFB processing can be seen in Figure 7.

CONCLUSIONS

Only gate-to-gate LCA analysis, that is the process between receiving raw material (FFB) and the CPO storage tank, was the subject of the study. According to the LCA effect category, the oil purifier station (19×10^3 kg-CO_2eq), the continuous settling tank (15.6×10^3 kg-CO_2eq), and the vacuum dryer (19.1×10^3 kg-CO_2eq) have the highest hourly CO_2eq emissions. The vacuum dryer is then the hot spot.

With 59.7 kg-SO_4eq, the CPO storage (storage tank) has the highest potential impact of acidification, and with 24.3 kg-PO_4^{3-}eq, the CPO tank has the highest eutrophication emission values. Additionally, a lot of water is used, particularly at the vacuum dryer (5.38 m³/ton of FFB), the oil purifier (3.9 m³/ton), and the CPO tank (5.42 m³/ton). The total amount of water used to process 60 tons of FFB per hour is 11.9 m³/ton FFB.

Carbon emissions (CO_2eq) at each stage of the process are considerably influenced by the emission potentials of GWP, acidification, eutrophication, water footprint, and energy consumption, according to the LCA study of the inputs. All processing steps provide significant CO_2-eq emission values, although the CST, oil purifier, vacuum dryer, and CPO tank have the largest emission impacts (kg-CO_2eq) when compared to other stages.

In terms of managing environmental sustainability, taking into account the effects from gate to gate will greatly reduce the amount of pollution produced by the production of CPO. The usage of input and output energy in a process is directly impacted by life cycle management, particularly when processing FFB to produce CPO, which generates waste including palm kernels, fiber waste, EFB, and liquid waste. For sustainable palm oil plantations, these wastes should be utilized as organic fertilizer and as an energy source as best they can. By switching from non-renewable to sustainable energy sources, the overall emissions will be greatly decreased.

Every stage of the CPO production process consumes a significant quantity of energy, and a significant amount of energy-containing biomass is produced and wasted. The amount of pollution produced by the CPO mills, as indicated by CO_2-eq, will be greatly decreased by turning that biomass into energy and using it to generate heat and power.

Starting with sowing, planting, harvesting, and transportation to the CPO mill, followed by CPO distribution and final use, are the whole production processes of CPO production, including cradle-to-cradle LCA analysis. According to this study, the environmental impact of the mill is substantial. However, focusing solely on the mill will not address the environmental issues facing CPO. Therefore, it is recommended that the findings of this study be applied to the distribution and use of CPO as well as the full LCA from cradle to mill.

REFERENCES

1. Abdullah, N., & Sulaim, F. (2013). The oil palm wastes in Malaysia. *Biomass Now - Sustainable Growth and Use*. https://doi.org/10.5772/55302
2. Acaroĝlu, M., & Aydoĝan, H. (2012). Biofuels energy sources and future of biofuels energy in Turkey. *Biomass and Bioenergy*, *36*, 69–76. https://doi.org/10.1016/j.biombioe.2011.10.004
3. Agustiar, Bantacut, T., Romli, M., & Pramudya, B. (2020). The usage of oil palm biomass as a source of electricity generation in south west of aceh, Indonesia. *Plant Archives*, *20*(1), 1639–1644.
4. Agustiar, Bantacut, T., Romli, M., Pramudya, B., & Aulia, M. R. (2023). The potential of bio-try briquettes for biomass power plant in Aceh Province – Case study in South West Aceh , Indonesia. *Journal of Ecological Engineering, 24*(10), 115–124.
5. Ahmad, A., Buang, A., & Bhat, A. H. (2016). Renewable and sustainable bioenergy production from microalgal co-cultivation with palm oil mill effluent (POME): A review. *Renewable and Sustainable Energy Reviews*, *65*, 214–234. https://doi.org/10.1016/j.rser.2016.06.084
6. Al-Hamamre, Z., Saidan, M., Hararah, M., Rawajfeh, K., Alkhasawneh, H. E., & Al-Shannag, M. (2017). Wastes and biomass materials as sustainable-renewable energy resources for Jordan. *Renewable and Sustainable Energy Reviews*, *67*, 295–314. https://doi.org/10.1016/j.rser.2016.09.035
7. Alkusma, Y. M., Hermawan, H., & Hadiyanto, H. (2016). Pengembangan potensi energi Alternatif Dengan Pemanfaatan Limbah Cair Kelapa Sawit Sebagai Sumber Energi Baru Terbarukan Di Kabupaten Kotawaringin Timur. *Jurnal Ilmu Lingkungan*, *14*(2), 96. https://doi.org/10.14710/jil.14.2.96-102
8. Amelia, J. R. (2017). *Teknologi Pengelolaan Limbah Cair Dan Limbah Padat Secara Terintegrasi Untuk Mendukung Industri Kelapa Sawit Berkelanjutan*. https://repository.ipb.ac.id/handle/123456789/88647
9. Bantacut, T., & Romli, M. (2020). Development of energy self-sufficiency of agroindustry. *IOP Conference Series: Earth and Environmental Science*, *472*(1). https://doi.org/10.1088/1755-1315/472/1/012039
10. Bantacut, T. S. S. (2014). Application of cleaner production in palm oil mill: A case study at PT Perkebunan Nusantara IV Adolina Business Unit ... Application of Cleaner Production in Palm Oil Mill : A Case Study at PT Perkebunan Nusantara IV Adolina Business Unit. *Chemistry and Materials Research*, *6*(January), 178–188. http://www.researchgate.net/publication/280534614%0Awww.iiste.org
11. Bantacut, Tajuddin, & Novitasari, D. (2016). Energy and water self-sufficiency assessment of the white sugar production process in Indonesia using a complex mass balance model. *Journal of Cleaner Production*, *126*, 478–492. https://doi.org/10.1016/j.jclepro.2016.02.092
12. Bantacut, Tajuddin, & Pasaribu, H. (2015). Closed mass flows and energy self sufficiency in CPO production. *Hermaslin Pasaribu J Tek Ind Pert*, *25*(3), 215–226.
13. Bessou, C., & Pardon, L. (2016). Environmental impacts of palm oil products: What can we learn from LCA? *Indonesian Journal of Life Cycle Assessment and Sustainability*, *1*(1), 1–7. https://doi.org/10.52394/ijolcas.v1i1.2
14. Boulay, A., Hoekstra, A. Y., & Vionnet, S. (2013). *T © 2013*. 11926–11927.
15. Cappelli, A., Gigli, E., Romagnoli, F., Simoni, S., Blumberga, D., Palerno, M., & Guerriero, E. (2015). Co-digestion of macroalgae for biogas production: An LCA-based Environmental Evaluation. *Energy Procedia*, *72*, 3–10. https://doi.org/10.1016/j.egypro.2015.06.002
16. Chauhan, M. K., Varun, Chaudhary, S., Kumar, S., & Samar. (2011). Life cycle assessment of sugar industry: A review. *Renewable and Sustainable Energy Reviews*, *15*(7), 3445–3453. https://doi.org/10.1016/j.rser.2011.04.033
17. Dal Ferro, N., Cocco, E., Lazzaro, B., Berti, A., & Morari, F. (2016). Assessing the role of agri-environmental measures to enhance the environment in the Veneto Region, Italy, with a model-based

approach. *Agriculture, Ecosystems and Environment*, *232*, 312–325. https://doi.org/10.1016/j.agee.2016.08.010

18. Darojat, K., Hadi, W., & Rahayu, D. E. (2019). Life cycle assessment (LCA) utilization of oil palm empty fruit bunches as bioenergy. *AIP Conference Proceedings*, *2194*(December). https://doi.org/10.1063/1.5139751
19. Davis, C., Nikolíc, I., & Dijkema, G. P. J. (2009). Integration of life cycle assessment into agent-based modeling toward informed decisions on evolving infrastructure systems. *Journal of Industrial Ecology*, *13*(2), 306–325. https://doi.org/10.1111/j.1530-9290.2009.00122.x
20. Desinta Sawitri Giandadewi, Pertiwi Andarani, W. D. N. (2017). Potensi Dampak Lingkungan Dalam Sistem Produksi Minyak Kelapa Sawit Mentah (Crude Palm Oli-CPO) Dengan Menggunakan Metode Life Cycle Assesment (Eco-Indicator 99) (Studi Kasus PT. Sinar Mas Agro Resources And Technology Tbk). *Jurnal Teknik Lingkungan*, *327*(6), 1–10. http://ejournal-s1.undip.ac.id/index.php/tlingkungan
21. Dincer, I., & Bicer, Y. (2018). Life cycle assessment of energy. In *Comprehensive Energy Systems*, 1–5. https://doi.org/10.1016/B978-0-12-809597-3.00134-6
22. Er, A. C., Nor, R. R. M., & Rostam, K. (2011). Palm oil milling wastes and sustainable development. *American Journal of Applied Sciences*, *8*(5), 436–440. https://doi.org/10.3844/ajassp.2011.436.440
23. Espino, M. T. M., De Ramos, R. M. Q., & Bellotindos, L. M. (2019). Life cycle assessment of the oil palm production in the Philippines: A cradle to gate approach. *Nature Environment and Pollution Technology*, *18*(3), 709–718.
24. Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., & Suh, S. (2009). Recent developments in life cycle assessment. *Journal of Environmental Management*, *91*(1), 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018
25. Fiorese, G., Catenacci, M., Verdolini, E., & Bosetti, V. (2013). Advanced biofuels: Future perspectives from an expert elicitation survey. *Energy Policy*, *56*, 293–311. https://doi.org/10.1016/j.enpol.2012.12.061
26. Foo, K. Y., & Hameed, B. H. (2010). Insight into the applications of palm oil mill effluent: A renewable utilization of the industrial agricultural waste. *Renewable and Sustainable Energy Reviews*, *14*(5), 1445–1452. https://doi.org/10.1016/j.rser.2010.01.015
27. Faisal, M. F., & Mahidin, M. (2013). Biomass residue from palm oil mills in Aceh Province: A potential usage for sustainable energy. *International Journal on Advanced Science, Engineering and Information Technology*, *3*(3), 222. https://doi.org/10.18517/ijaseit.3.3.324
28. Garcia-Nunez, J. A., Ramirez-Contreras, N. E., Rodriguez, D. T., Silva-Lora, E., Frear, C. S., Stockle, C., & Garcia-Perez, M. (2016). Evolution of palm oil mills into bio-refineries: Literature review on current and potential uses of residual biomass and effluents. *Resources, Conservation and Recycling*, *110*, 99–114. https://doi.org/10.1016/j.resconrec.2016.03.022
29. Gerbens-Leenes. (2013). *Bioenergy and water*. Bioenergy and Water. https://doi.org/10.2790/94402
30. Gobi, K., & Vadivelu, V. M. (2013). By-products of palm oil mill effluent treatment plant - A step towards sustainability. *Renewable and Sustainable Energy Reviews*, *28*, 788–803. https://doi.org/10.1016/j.rser.2013.08.049
31. Goedkoop, M., & Spriensma, R. (2001). The eco-indicator 99 - A damage oriented method for life cycle impact assessment. *Assessment*, *January 2001*, 144.
32. Gunarso, P., Hartoyo, M. E., Agus, F., & Killeen, T. J. (2013). Oil palm and land use change in Indonesia, Malaysia and Papua New Guinea. *Reports from the Technical Panels of RSPOs 2nd Greenhouse Gas Working Group*, 29–64. http://www.rspo.org/file/GHGWG2/4_oil_palm_and_land_use_change_Gunarso_et_al.pdf
33. Hambali, E., & Rivai, M. (2017). The potential of palm oil waste biomass in Indonesia in 2020 and 2030. *IOP Conference Series: Earth and Environmental Science*, *65*(1). https://doi.org/10.1088/1755-1315/65/1/012050
34. Hamzah, N., Tokimatsu, K., & Yoshikawa, K. (2019). Solid fuel from oil palm biomass residues and municipal solid waste by hydrothermal treatment for electrical power generation in Malaysia: A review. *Sustainability (Switzerland)*, *11*(4), 1–23. https://doi.org/10.3390/su11041060
35. Harahap, F., Leduc, S., Mesfun, S., Khatiwada, D., Kraxner, F., & Silveira, S. (2019). Opportunities to optimize the palm oil supply chain in Sumatra, Indonesia. *Energies*, *12*(3). https://doi.org/10.3390/en12030420
36. Haryanti, A., Norsamsi, N., Fanny Sholiha, P. S., & Putri, N. P. (2014). Studi pemanfaatan limbah padat kelapa sawit. *Konversi*, *3*(2), 20. https://doi.org/10.20527/k.v3i2.161
37. Hayashi, K. (2007). *Schematic flow of palm oil industry*, *7*, 646–651.
38. Hidayat, L., Surawan, F. E. D., & Raja, A. H. L. (2017). Kajian sumber energi pada pengolahan kelapa sawit menjadi crude palm oil (Cpo) Di Pt. Alno Agro Utama Sumindo Oil Mill, Bengkulu Utara. *Agrointek*, *11*(2), 75. https://doi.org/10.21107/agrointek.v11i2.3175
39. Hischier, R., Weidema, B., Althaus, H.-J., Bauer, C., Doka, G., Dones, R., Frischknecht, R., Hellweg, S.,

Humbert, S., Jungbluth, N., Köllner, T., Loerincik, Y., Margni, M., & Nemecek, T. (2010). Implementation of Life Cycle Impact Assessment Methods Data v2.2 (2010). *Ecoinvent Report No. 3*, *3*, 176. https://www.ecoinvent.org/files/201007_hischier_weidema_implementation_of_lcia_methods.pdf

40. Hoekstra, A. Y. (2016). A critique on the water-scarcity weighted water footprint in LCA. *Ecological Indicators*, *66*, 564–573. https://doi.org/10.1016/j.ecolind.2016.02.026
41. Hosseini, S. E., & Wahid, M. A. (2014). Utilization of palm solid residue as a source of renewable and sustainable energy in Malaysia. *Renewable and Sustainable Energy Reviews*, *40*, 621–632. https://doi.org/10.1016/j.rser.2014.07.214
42. Hosseini, S. E., & Wahid, M. A. (2015). Pollutant in palm oil production process. *Journal of the Air and Waste Management Association*, *65*(7), 773–781. https://doi.org/10.1080/10962247.2013.873092
43. Hosseini, S. E., Wahid, M. A., & Aghili, N. (2013). The scenario of greenhouse gases reduction in Malaysia. *Renewable and Sustainable Energy Reviews*, *28*(December 1997), 400–409. https://doi.org/10.1016/j.rser.2013.08.045
44. Husain, Z., Zainal, Z. A., & Abdullah, M. Z. (2003). Analysis of biomass-residue-based cogeneration system in palm oil mills. *Biomass and Bioenergy*, *24*(2), 117–124. https://doi.org/10.1016/S0961-9534(02)00101-0
45. IPCC. (2006). 2006 IPCC Guidelines for National Greenhouse Inventories – A primer, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Miwa K., Srivastava N. and Tanabe K. *Iges*, 20.
46. Izah, S. C., Ohimain, E. I., & Angaye, T. C. N. (2016). Potential thermal energy from palm oil processing solid wastes in Nigeria: mills consumption and surplus quantification. *British Journal of Renewable Energy*, *01*(01), 39–45.
47. Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., & Rosenbaum, R. (2003). IMPACT 2002+: A new life cycle impact assessment methodology. *International Journal of Life Cycle Assessment*, *8*(6), 324–330. https://doi.org/10.1007/BF02978505
48. Kar, Y., & Tekeli, Y. (2008). The potential of biomass residues in Turkey and their importance as energy resources. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, *30*(6), 483–493. https://doi.org/10.1080/15567030600828974
49. Kaygusuz, K. (2009). Bioenergy as a clean and sustainable fuel. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, *31*(12), 1069–1080. https://doi.org/10.1080/15567030801909839
50. Kelly-Yong, T. L., Lee, K. T., Mohamed, A. R., & Bhatia, S. (2007). Potential of hydrogen from oil palm biomass as a source of renewable energy worldwide. *Energy Policy*, *35*(11), 5692–5701. https://doi.org/10.1016/j.enpol.2007.06.017
51. Klöpffer, W. (2006). The Hitch Hiker´s Guide to LCA - An orientation in LCA methodology and application. *The International Journal of Life Cycle Assessment*, *11*(2), 142–142. https://doi.org/10.1065/lca2006.02.008
52. Klöpffer, W., & Grahl, B. (2014). *Life cycle assessment (LCA): A guide to best practice.* Life Cycle Assessment (LCA): A Guide to Best Practice. https://doi.org/10.1002/9783527655625
53. Kospa, H. S. D., Lulofs, K. R. D., & Asdak, C. (2017). Estimating water footprint of palm oil production in PTP Mitra Ogan Baturaja, South Sumatera. *International Journal on Advanced Science, Engineering and Information Technology*, *7*(6), 2115–2121. https://doi.org/10.18517/ijaseit.7.6.2451
54. Kramanandita et al. (2014). Dampak Perubahan Efisiensi Di Stasiun Sterilisasi Pabrik Kelapa Sawit Menggunakan Model Input - Output Leontief Impact of Efficiency Changes At Palm Oil Mill Sterilization Station Using Leontiefinput-Output Model. *Journal of Industrial Research*, *8*(2), 129–134.
55. Kramanandita, R., Bantacut, T., Romli, M., & Makmoen, M. (2014). Utilizations of palm oil mills wastes as source of energy and water in the production process of crude palm oil. *Chemistry and Materials Research*, *6*(8), 46–53.
56. Kurka, T., & Blackwood, D. (2013). Participatory selection of sustainability criteria and indicators for bioenergy developments. *Renewable and Sustainable Energy Reviews*, *24*, 92–102. https://doi.org/10.1016/j.rser.2013.03.062
57. Ling-Chin, J., Heidrich, O., & Roskilly, A. P. (2016). Life cycle assessment (LCA) - From analysing methodology development to introducing an LCA framework for marine photovoltaic (PV) systems. *Renewable and Sustainable Energy Reviews*, *59*, 352–378. https://doi.org/10.1016/j.rser.2015.12.058
58. Mahlia, T. M. I., Abdulmuin, M. Z., Alamsyah, T. M. I., & Mukhlishien, D. (2001). An alternative energy source from palm wastes industry for Malaysia and Indonesia. *Energy Conversion and Management*, *42*(18), 2109–2118. https://doi.org/10.1016/S0196-8904(00)00166-7
59. McManus, M. C., & Taylor, C. M. (2015). The changing nature of life cycle assessment. *Biomass and Bioenergy*, *82*, 13–26. https://doi.org/10.1016/j.biombioe.2015.04.024
60. Menoufi, K. A. I. (2011). An overview on life cycle impact assessment (LCIA) methodologies: State of the art. *Disertation*.
61. Nasution, M. A., Herawan, T., & Rivani, M. (2014). Analysis of palm biomass as electricity from palm oil mills in north sumatera. *Energy*

Procedia, *47*, 166–172. https://doi.org/10.1016/j.egypro.2014.01.210

62. Noviantari, K., Hasyim, A. I., Rosanti, N., Agribisnis, J., Pertanian, F., Lampung, U., Prof, J., & Brojonegoro, S. (2015). *SCM_13320-ID-analisis-rantai-pasok-dan-nilai-tambah-agroindustri-kopi-luwak-di-provinsi-lampu*. *3*(1), 10–17.
63. Ohimain, E. I., & Izah, S. C. (2014). Potential of biogas production from palm oil mills' effluent in Nigeria. *Sky Journal of Soil Science and Environmental Management*, *3*(5), 50–58. http://www.skyjournals.org/SJSSEM
64. Pandia, E. B., Hernawati, H., Jari, T., & Kahar, A. (2020). Pengaruh laju alir terhadap COD, BOD dan VFA pada Pengolahan Limbah Cair Pabrik Kelapa Sawit (LCPKS) dalam Bioreaktor Anaerobik. *Jurnal Chemurgy*, *4*(2), 30. https://doi.org/10.30872/cmg.v4i2.4591
65. Phang, K. Y., & Lau, S. W. (2017). A survey on the usage of biomass wastes from palm oil mills on sustainable development of oil palm plantations in Sarawak. *IOP Conference Series: Materials Science and Engineering*, *206*(1). https://doi.org/10.1088/1757-899X/206/1/012091
66. Prasertsan, S., & Prasertsan, P. (1996). Biomass residues from palm oil mills in Thailand: An overview on quantity and potential usage. *Biomass and Bioenergy*, *11*(5), 387–395. https://doi.org/10.1016/S0961-9534(96)00034-7
67. Rahayu, D. E., Nasarani, D., Hadi, W., & Wrjodirjo, B. (2018). Potential of biomass residues from oil palm agroindustry in Indonesia. *MATEC Web of Conferences*, *197*, 1–4. https://doi.org/10.1051/matecconf/201819713008
68. Rega, F. V., & Ferranti, P. (2019). Life cycle assessment of coffee production in time of global change. In *Encyclopedia of Food Security and Sustainability* (pp. 497–502). Elsevier. https://doi.org/10.1016/B978-0-08-100596-5.22141-0
69. Reijnders, L., & Huijbregts, M. A. J. (2008). Palm oil and the emission of carbon-based greenhouse gases. *Journal of Cleaner Production*, *16*(4), 477–482. https://doi.org/10.1016/j.jclepro.2006.07.054
70. Sadhukhan, J., Martinez-Hernandez, E., Amezcua-Allieri, M. A., Aburto, J., & Honorato S, J. A. (2019). Economic and environmental impact evaluation of various biomass feedstock for bioethanol production and correlations to lignocellulosic composition. *Bioresource Technology Reports*, *7*(May). https://doi.org/10.1016/j.biteb.2019.100230
71. Scarlat, N., & Dallemand, J. F. (2011). Recent developments of biofuels/bioenergy sustainability certification: A global overview. *Energy Policy*, *39*(3), 1630–1646. https://doi.org/10.1016/j.enpol.2010.12.039
72. Schmidt, J. H. (2010). LCA applied to palm oil. *Most*, *March*.
73. Science, E. (2024). *Mass balance of palm waste energy potential in palm oil processing in South West Aceh , Indonesia Mass balance of palm waste energy potential in palm oil processing in South West Aceh , Indonesia*. https://doi.org/10.1088/1755-1315/1297/1/012076
74. Shuit, S. H., Tan, K. T., Lee, K. T., & Kamaruddin, A. H. (2009). Oil palm biomass as a sustainable energy source: A Malaysian case study. *Energy*, *34*(9), 1225–1235. https://doi.org/10.1016/j.energy.2009.05.008
75. Siangjaeo, S., Gheewala, S. H., Unnanon, K., & Chidthaisong, A. (2011). Implications of land use change on the life cycle greenhouse gas emissions from palm biodiesel production in Thailand. *Energy for Sustainable Development*, *15*(1), 1–7. https://doi.org/10.1016/j.esd.2011.01.002
76. Siddiquee, M. N., & Rohani, S. (2011). Lipid extraction and biodiesel production from municipal sewage sludges: A review. *Renewable and Sustainable Energy Reviews*, *15*(2), 1067–1072. https://doi.org/10.1016/j.rser.2010.11.029
77. Singh, A., Olsen, S. I., & Pant, D. (2013). Importance of life cycle assessment of renewable energy sources. *Green Energy and Technology*, *0*(9781447153634), 1–11. https://doi.org/10.1007/978-1-4471-5364-1_1
78. Steubing, B., Wernet, G., Reinhard, J., Bauer, C., & Moreno-Ruiz, E. (2016). The ecoinvent database version 3 (part II): analyzing LCA results and comparison to version 2. *International Journal of Life Cycle Assessment*, *21*(9), 1269–1281. https://doi.org/10.1007/s11367-016-1109-6
79. Stichnothe, H., & Schuchardt, F. (2010). Comparison of different treatment options for palm oil production waste on a life cycle basis. *International Journal of Life Cycle Assessment*, *15*(9), 907–915. https://doi.org/10.1007/s11367-010-0223-0
80. Stichnothe, H., & Schuchardt, F. (2011). Life cycle assessment of two palm oil production systems. *Biomass and Bioenergy*, *35*(9), 3976–3984. https://doi.org/10.1016/j.biombioe.2011.06.001
81. Subramaniam, V., May, C. Y., Muhammad, H., Hashim, Z., Tan, Y. A., & Wei, P. C. (2010a). Life cycle assessment of the production of crude palm kernel oil (part 3a). *Journal of Oil Palm Research*, *22*(DECEMBER), 904–912.
82. Subramaniam, V., May, C. Y., Muhammad, H., Hashim, Z., Tan, Y. A., & Wei, P. C. (2010b). Life cycle assessment of the production of crude palm oil (part 3). *Journal of Oil Palm Research*, *22*(DECEMBER), 895–903.
83. Sugiyono, A. (2008). Peluang pemanfaatan biodiesel dari alternatif pengganti minyak solar. *Prospek Pengembangan Bio-Fuel Sebagai Substitusi Bahan Bakar Minyak*, 29–40. ttp://www.geocities.ws/

markal_bppt/publish/biofbbm/bisugi.pdf.

84. Susanto, J. P., Santoso, A. D., & Suwedi, N. (2017). Perhitungan potensi limbah padat kelapa sawit untuk sumber energi terbaharukan dengan metode LCA. *Jurnal Teknologi Lingkungan*, *18*(2), 165. https://doi.org/10.29122/jtl.v18i2.2046
85. Van Rikxoort, H., Schroth, G., Läderach, P., & Rodríguez-Sánchez, B. (2014). Carbon footprints and carbon stocks reveal climate-friendly coffee production. *Agronomy for Sustainable Development*, *34*(4), 887–897. https://doi.org/10.1007/s13593-014-0223-8
86. Vijaya, S., Ma, A. N., Choo, Y. M., & Nik Meriam, N. S. (2008). Life cycle inventory of the production of crude palm oil - A gate to gate case study of 12 palm oil mills. *Journal of Oil Palm Research*, *20*(JUNE), 484–494.
87. Wardenaar, T., Van Ruijven, T., Beltran, A. M., Vad, K., Guinée, J., & Heijungs, R. (2012). Differences between LCA for analysis and LCA for policy: A case study on the consequences of allocation choices in bio-energy policies. *International Journal of Life Cycle Assessment*, *17*(8), 1059–1067. https://doi.org/10.1007/s11367-012-0431-x
88. Wicke, B., Dornburg, V., Junginger, M., & Faaij, A. (2008). Different palm oil production systems for energy purposes and their greenhouse gas implications. *Biomass and Bioenergy*, *32*(12), 1322–1337. https://doi.org/10.1016/j.biombioe.2008.04.001
89. Wu, Q., Qiang, T. C., Zeng, G., Zhang, H., Huang, Y., & Wang, Y. (2017). Sustainable and renewable energy from biomass wastes in palm oil industry – A case study in Malaysia. *International Journal of Hydrogen Energy*, *42*(37), 23871–23877. https://doi.org/10.1016/j.ijhydene.2017.03.147
90. Yusoff, S. (2006). Renewable energy from palm oil - Innovation on effective utilization of waste. *Journal of Cleaner Production*, *14*(1), 87–93. https://doi.org/10.1016/j.jclepro.2004.07.005
91. Yusoff, S., & Hansen, S. B. (2007). Feasibility study of performing an life cycle assessment on crude palm oil production in Malaysia. *International Journal of Life Cycle Assessment*, *12*(1), 50–58. https://doi.org/10.1065/lca2005.08.226
92. Yusuf, M. A., Romli, M., Suprihatin, & Wiloso, E. I. (2019). Carbon footprint of semi-mechanical sago starch production. *Journal of Ecological Engineering*, *20*(11), 159–166. https://doi.org/10.12911/22998993/110813
93. Zhuo, L., Feng, B., & Wu, P. (2020). Water footprint study review for understanding and resolving water issues in china. *Water (Switzerland)*, *12*(11), 1–14. https://doi.org/10.3390/w12112988
94. Zulkifli, H., Halimah, M., Chan, K. W., Choo, Y. M., & Mohd Basri, W. (2010). Life cycle assessment for oil palm fresh fruit bunch production from continued land use for oil palm planted on mineral soil (part 2). *Journal of Oil Palm Research*, *22*, 887–894.