九州工業大学学術機関リポジトリ
Kyutacar
Kyushu Institute of Technology Academic Repository

Life Cycle Assessment for Bioethanol Production from Oil Palm Frond Juice in an Oil Palm Based Biorefinery

著者	Yusof Siti Jamilah Hanim Mohd, Roslan Ahmad Muhaimin, Khairul Nadiah Ibrahim, Abdullah Sharifah Soplah Syed, Zakaria Mohd Rafein, Hassan Mohd Ali, Shirai Yoshihito
journal or publication title	Sustainability
volume	11
number	24
page range	6928-1-6928-14
year	2019-12-05
URL	http://hdl.handle.net/10228/00007650

doi: info:doi/10.3390/su11246928

sustainability

MDPI

Article

Life Cycle Assessment for Bioethanol Production from Oil Palm Frond Juice in an Oil Palm Based Biorefinery

Siti Jamilah Hanim Mohd YUSOF [1,2], Ahmad Muhaimin Roslan [3,4,*], Khairul Nadiah Ibrahim [5], Sharifah Soplah Syed ABDULLAH [5], Mohd Rafein Zakaria [3,4], Mohd Ali Hassan [1,3] and Yoshihito Shirai [6]

[1] Department of Food and Process Engineering, Faculty of Engineering, Universiti Putra Malaysia, UPM Serdang 43400, Malaysia; jamilahhanim@unimap.edu.my (S.J.H.M.Y.); alihas@upm.edu.my (M.A.H.)
[2] School of Bioprocess Engineering, Universiti Malaysia Perlis, Perlis 02600, Malaysia
[3] Department of Bioprocess Technology, Faculty of Biotechnology and Biomolecular Sciences, Universiti Putra Malaysia, UPM Serdang 43400, Malaysia; mohdrafein@upm.edu.my
[4] Laboratory of Biopolymer and Derivatives, Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, UPM Serdang 43400, Malaysia
[5] Universiti Kuala Lumpur Branch Campus Malaysian Institute of Chemical and Bioengineering Technology (UniKL MICET), Lot 1988, Kawasan Perindustrian, Bandar Vendor, Alor Gajah 78000, Malaysia; khairulnadiah@unikl.edu.my (K.N.I.); sharifahsoplah@unikl.edu.my (S.S.S.A.)
[6] Department of Biological Functions and Engineering, Graduate School of Life Science and System Engineering, Kyushu Institute of Technology, Fukuoka 808-0916, Japan; shirai@life.kyutech.ac.jp
* Correspondence: ar_muhaimin@upm.edu.my

Received: 24 September 2019; Accepted: 21 October 2019; Published: 5 December 2019

check for updates

Abstract: A study was conducted to estimate the possible environmental impacts arising from the generation of bioethanol from oil palm frond sugar juice in a theoretical oil palm based biorefinery model. A life cycle assessment (LCA) with the gate-to-gate approach was performed with the aid of SimaPro version 8.0 whereby ten impact categories were evaluated. The scope included frond collection and transportation, frond sugar juice extraction, and bioethanol fermentation and purification. Evaluation on the processes involved indicated that fermentation contributed to the environmental problems the most, with a contribution range of 52% to 97% for all the impact categories. This was due to a substantial usage of nutrient during this process, which consumes high energy for its production thus contributing a significant burden to the surrounding. Nevertheless, the present system offers a great option for biofuel generation as it utilizes sugar juice from the readily available oil palm waste. Not only solving the issue of land utilization for feedstock cultivation, the enzymatic saccharification step, which commonly necessary for lignocellulosic sugar recovery could also be eliminated.

Keywords: life cycle assessment; oil palm frond; oil palm frond juice; bioethanol

1. Introduction

The total world energy consumption is increasing every year with fossil fuel as the major source of energy supply. In 2015, the total world energy consumption was 575 quadrillion British thermal unit (Btu), and is projected to achieve 736 quadrillion Btu in 2040 [1]. Furthermore, with existing technologies and consumption patterns, the world energy demand is expected to be doubled by 2050 [2]. In order to compensate the increasing energy demand and to lessen the reliability on the depleting fossil fuel, efforts have been directed on the discovery of alternative fuels from renewable resources. According to International Energy Outlook 2016 (IEO 2016) [3], the introduction of several government strategies and incentives promoting the use of alternative energy sources has led to a rapid progress of renewable energy, with an average rate of 2.6%/year. One of the common technologies for biofuel generation is through the application of microorganisms, which utilize carbohydrate as a carbon source. As compared to first generation biofuel, the production of biofuel from non-food feedstocks such as agricultural wastes is more preferable since these wastes are abundantly available and mostly underutilized, as well as to avoid competition with food [4–6].

Oil palm frond (OPF) is among the largest group of oil palm waste with nearly 21.03 million tonnes (dry weight basis) generated for 95.38 million tonnes of fresh fruit bunch processed in 2014 [7]. It was expected that 56 million tonnes/year of OPF would be produced in Malaysia alone during replanting by 2020 [8]. Due to its high carbohydrates and nourishing constituents, OPF could serve as a substrate for the production of biofuels, bio-based chemicals, biofertilizer, and animal feed [9–12]. Furthermore, OPF petiole juice consists of high glucose content and can simply be extracted by conventional sugarcane pressing method [13–15]. On the other hand, OPF-pressed fiber, which is the residual part following pressing, contains a substantial amount of cellulose, approximately 33–45%, and can be further hydrolyzed into simple sugars through pretreatment and enzymatic hydrolysis [14–19].

In the previous study, the incorporation of a biorefinery with an existing palm oil mill was demonstrated promising for bioethanol production upscaling due to the availability of surplus fuel to accommodate the biorefinery [9]. Recognizing that the environmental criteria must also be considered in the selection of the biofuel production process [4], a life cycle assessment (LCA) was performed in the present study with slight modifications on the previous model [9]. LCA is the common method in assessing the environmental performance of a process. Many LCA studies have been conducted on biofuel production from various feedstocks and lignocellulosic materials over the past years [4,5,20]. It was reported that bioethanol production can contribute to different environmental impacts, depending on the raw material used and process involved [4]. However, the most highlighted points were the impacts associated with feedstock cultivation (e.g. land use) and harvesting for first generation bioethanol [21–23], and sugar recovery for lignocellulosic bioethanol production [24,25] due to chemical (fertilizer), enzyme, and fossil fuel usage. Therefore, the aim of the present study was to reduce the environmental impact from bioethanol production by proposing a new model utilizing sugars from OPF petiole juice.

2. Materials and Methods

2.1. Process Description

The proposed model was developed based on a study by Abdullah et al. [9]. Four nearby palm oil mills were selected for the construction of the model with one of the mills integrated with a biorefinery for bioethanol production. Figure 1 depicts the complete material balance for the extraction of fermentable sugars from OPF petiole juice and subsequent bioethanol production at the biorefinery OPF petiole sugars were initially produced through pressing and saccharification processes at the individual mill, whereby all the energy required for this process was obtained from the extra energy supplied by the co-generation system. Therefore, the selection of the palm oil mill to set up the biorefinery was determined by the adequacy of excess energy available at the mill to support the bioethanol production [9]. Nonetheless, in the present study, several modifications were done to improve its environmental performance. Only sugars deriving from OPF petiole juice were used in ethanol fermentation whereas the pressed fiber was sold to other company as feedstock. Hence, saccharification step, which was reported to cause extensive harmful impact to the environment due to consumption of enzyme and chemicals [4,5], was removed. Another modification was to simultaneously treat the stillage with the palm oil mill effluent in the anaerobic treatment system to enhance biogas production. Apart from these adjustments, the remaining process was similar with those proposed earlier [9].

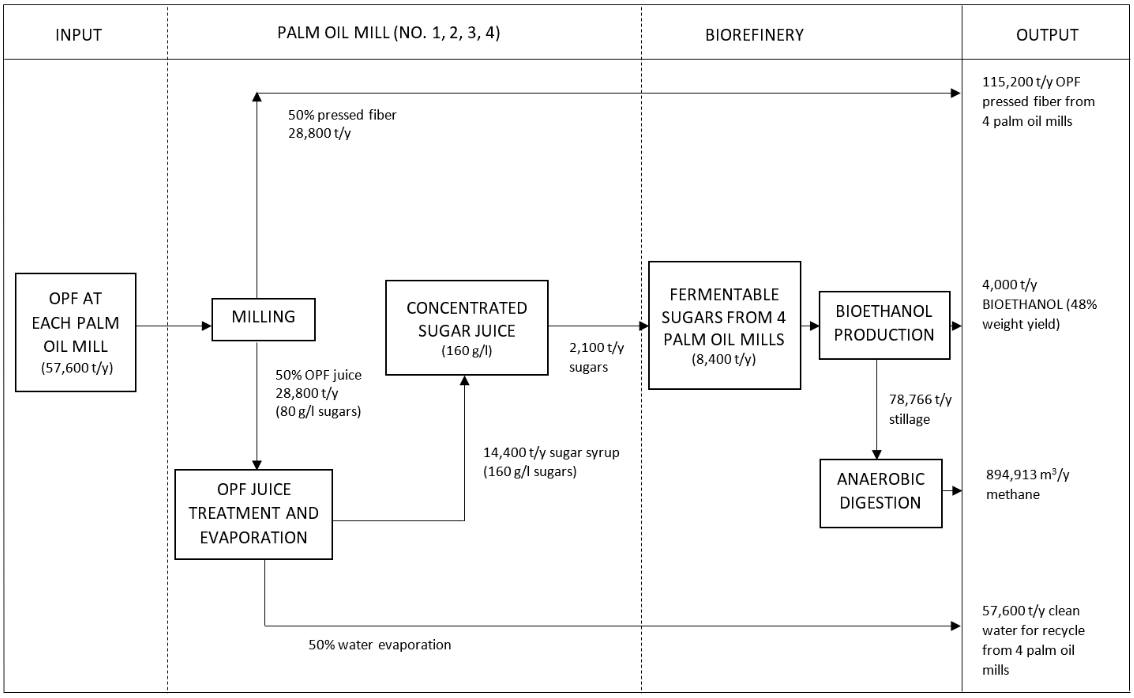

Figure 1. Overall mass balance for fermentable sugars and bioethanol production from oil palm frond (OPF) petiole sugar juice.

2.1.1. Collection and Transportation of OPF Petioles and Sugar Juice

It was estimated that with the average processing capacity of 240,000 tonnes of fresh fruit bunches (FFB) per mill in 2013, 57,600 tonnes of OPF petioles were generated [9]. Only the petiole part was collected as it contains high sugars, whereas the remaining leafy part was left at the plantation for soil nourishment [15]. The OPF petioles were conveyed from the plantation to the mills with average distance of 15 km. The transportation of OPF petioles only required 5% of the total energy as it was simultaneously performed with the transportation of FFB by attaching a special cart to the truck which carried FFB from plantation to the mill [9,26]. Meanwhile, concentrated sugar syrup was collected from four palm oil mills and transported to a proposed biorefinery plant which was located at one of the four mills, using 20 tonnes truck capacity. The distance between each mill was projected to be within 80 km radius to generate an economically attractive model with an acceptable transportation cost [9,12].

2.1.2. Juice Extraction and Treatment

The extraction of sugars from the frond and its treatment was conducted at each mill. The petioles were air-blown to remove any dust on its surface prior to pulverization to separate the fiber and the juice content. It was estimated that 500 g of OPF juice can be extracted from 1 kg of petioles [9,15,27]. Therefore, 28,800 tonnes/year of OPF juice was produced, together with an equal amount of pressed fiber. In order to facilitate a cost-effective transportation to the biorefinery plant, the OPF juice is further treated by removing 50% of its volume using rotary evaporator. This resulted in a concentrated juice with a density of 1100 kg/m^3 [9]. In total, 14,400 tonnes/year of sugar syrup are produced at each mill, which is equivalent to glucose content of 2100 tonnes and a concentration of approximately 160 g/L. This is followed by transportation of concentrated sugar juice to the particular mill located at the biorefinery. Hence, a total of 8400 tonnes/year of sugars could be collected from four mills involved in this model. In addition, a total of 115,200 tonnes/year of OPF pressed fiber could be generated and sold to generate more income for the biorefinery.

2.1.3. Ethanol Fermentation and Purification

The concentrated sugar syrup from four palm oil mills was combined at a biorefinery plant located at one of the four mills for bioethanol production. Overall, about 8400 tonnes of glucose can be collected annually from the four mills, and used for bioethanol production. Figure 2 illustrates the process flow diagram for the bioconversion of OPF petiole sugar juice into ethanol. Process simulation was conducted using Superpro Designer software version 9.5 by Intelligent Inc., Scotch Plain, New Jersey, USA at suitable operating conditions [9,12,13]. The design basis was 28 tonnes of OPF sugar juice per batch with maximum predicted production batches of 296 per year. Sterilization of the concentrated sugar solution was initially performed at 121 °C for 30 min at 0.6 MPa, followed by subsequent cooling to 31.9 °C to preserve the sugars and avoid contamination [28]. Initial inoculum concentration of *Saccharomyces cerevisiae* was fixed at 10% of biomass quantity per total amount of cultivation media. The fermentation was conducted in a bioreactor at 30 °C for 24 h with the addition of urea as nitrogen source, thereby producing ethanol and carbon dioxide. With 48% conversion yield, it was estimated that 4000 tonnes/year of ethanol can be generated from 8400 tonnes of glucose. The separation of solid and liquid fractions in the fermentation broth was performed by a disc stack centrifuge at a maximum throughput of 250 m^3/h for 4 h. The supernatant containing bioethanol was channeled to a continuous distillation, rectification, and stripping systems to further purify the ethanol. The solid residue which mainly comprised of yeast cells could be reinoculated in the next fermentation [29]. Due to azeotropic properties of ethanol/water mixtures, the separation was limited to a purity of only around 96% [30]. Molecular sieve drying was applied to achieve further water separation, resulting in 98.9% of anhydrous bioethanol [31].

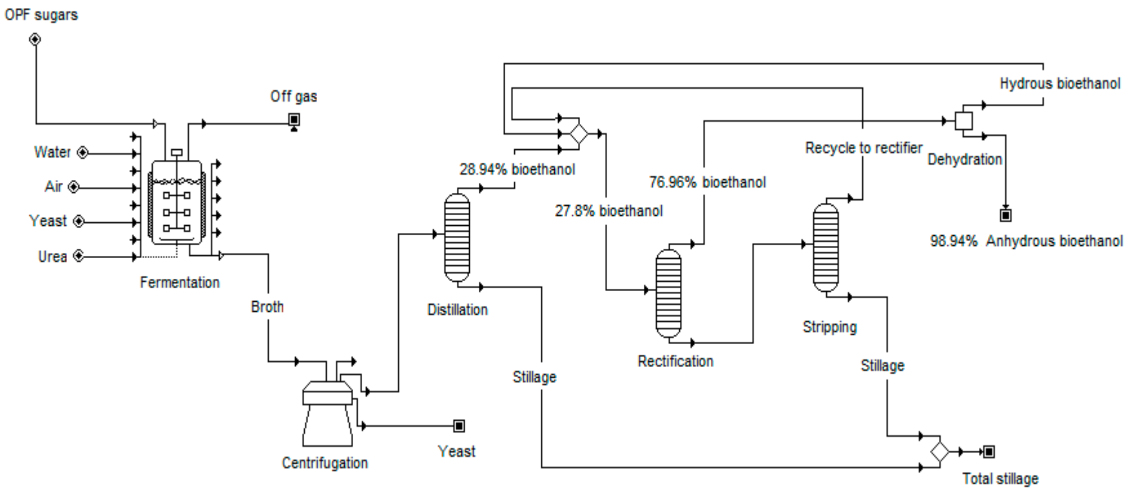

Figure 2. Process flow diagram of anhydrous bioethanol production via the bioconversion of OPF petiole sugar juice at the biorefinery.

2.1.4. Waste Management

Stillage, also known as vinasse, is an aqueous residue of ethanolic distillation with dark-brown color, acidic pH and high Chemical Oxygen Demand (COD) values, which make it dangerous to the environment. It was reported that the amount of stillage production was about 10–20 times that of ethanol produced [32,33], with a COD range of 27.5–299.3 kg/m^3, depending on the type of raw materials and the operating conditions in the ethanol production plant [34]. The initial separation of suspended solids in the stillage that contained yeast and other materials was commonly performed prior to other treatments. This solid part can be dried and sold as a high-value animal feed called dried distiller grain (DDG) or dried distiller grain with solubles (DDGS) [30,33]. However, DDGS production consumes high energy, approximately the same amount of energy as that of the entire bioethanol production [33]. Furthermore, the stillage produced from non-food substrate was reported to have low nutritive values, thus would not be suitable for animal feed application [35]. Therefore, in the present study, the stillage was combined in the existing anaerobic system for treating palm oil mill effluent to reduce the high energy consuming steps as well as to increase the biogas generation. Many studies have demonstrated the potential of using stillage for the generation of biogas whereby over 67% and 90% reduction of COD and Biochemical Oxygen Demand (BOD) [34] can be achieved, respectively, with average methane yield of more than 0.25 L/g COD [30]. On top of that, anaerobic digestion was also proven to be the most efficient stillage treatment method to decrease the environmental effect as compared to fertigation, concentration, and combustion [34]. In the present study, a total of 78,766 tonnes/year or 89,491 m^3/year of stillage was generated with the production of 4000 tonnes of bioethanol. Assuming that the biochemical methane potential of stillage in the present study is similar to that of stillage from cellulosic feedstock, which is approximately 10 mL methane at STP $(\text{mL stillage})^{-1}$ [35], it was estimated that 894,913 m^3/year of methane can be produced from this amount of stillage.

2.1.5. Energy Consumption

Cogeneration is a process that simultaneously produces two forms of energy using one source of fuel [36]. In palm oil mill, steam and electricity were produced from the combustion of oil palm biomass. Self-generated energy is a common practice at most palm oil mills, hence no additional external energy is required. In fact, the amount of energy produced is excessive; as only a small quantity is required for FFB processing [36]. Cogeneration system in palm oil mill consists of boiler, turbine and backpressure receiver [36]. Biomass fiber and shell obtained after oil extraction was returned to the boiler as biofuel. It was reported that for the mill capacity of 240,000 tonnes/year of FFB processed, a total of 55,200 tonnes of mesocarp fiber and shell were burnt in the boiler at a mixing ratio of 0.66:0.34 [9]. This amount of biofuel would produce approximately 299,325 tonnes of high pressure steam (20 bars, 300 °C) at boiler efficiency of 77.4% [36]. High pressure steam will move the turbine and generate 7.72 GWh of electricity at turbine efficiency of 77.4%. The backpressure receiver will collect the low pressure steam (3 bars, 130 °C) and channel it for FFB processing such as sterilization, digester, depericarper, and kernel dryer [36].

Assuming that each tonne of FFB processing consumes 17 kWh of electricity, a total of 4.08 GWh/year of electricity is required [37]. Whereas, approximately 510–650 kg of low pressure steam were used for processing of one tonne of FFB [9,36]. Therefore, there was an excess electricity of 3.64 GWh/year and 176,925 tonnes of steam that could be used to support the sugar recovery and bioethanol refinery. Energy requirement for bioethanol production was calculated using values from previous studies with sugar cane juice as baseline (Table 1), and is summarized in Table 2. Approximately 0.92 GWh/year of electricity was required for milling and juice extraction, with power demand of 16 kWh per tonne of OPF [38]. The three multiple effects evaporation system evaporator requires 4988 tonnes of steam/year to concentrate the OPF petiole juice, producing 14,400 tonnes/year of sugar syrup. Steam generated from the cogeneration system is used as thermal energy source in the first evaporation effect, separating part of the water in the juice that is used as heating source for the next evaporation effect [38]. Bioethanol production consumes 0.1 GWh/year of electricity and 4696 tonnes/year of steam during sterilization and fermentation, while ethanol purification involved steam utilization of 13,005 tonnes/year to produce 4000 tonnes of bioethanol. In total, 1.02 GWh of electricity and 22,689 tonnes of steam were needed annually to run the bioethanol biorefinery. Since the amount of surplus energy available at the mill was higher than these values, it can be utilized to run the bioethanol biorefinery.

Table 1. Literature data for the calculation of the energy requirement for bioethanol production from OPF petiole sugar juice at integrated biorefinery plant.

Description	Value	Reference
Power demand for OPF preparation and juice extraction	16 kWh/t OPF	[38]
Steam demand for OPF juice evaporation (three multiple effects evaporators)	86.6 kg/t OPF	[9]
Steam demand for sterilization of sugar syrup	563 kg/t sugar	[9]
Steam demand for distillation and dehydration of hydrous bioethanol	2.55 kg/l bioethanol	[38]
Power demand for bioethanol production	12 kWh/t sugar	[38,39]

Table 2. Estimated energy requirement for bioethanol production from OPF petiole sugar juice.

Process	Electricity Consumption (GWh/year)	Steam Consumption (tonne/year)
Milling and juice extraction	0.92	-
Juice pretreatment	-	4988
Fermentation	0.10	4696
Ethanol purification	-	13,005
Total	1.02	22,689

2.2. *Life Cycle Assessment (LCA)*

LCA is a tool or process to assess the possible impacts to the surrounding from a product, process or activities, by considering the whole supply chain of the product and raw materials involved including transportation and final dumping. It was conducted according to the standard outline provided by the International Organization for Standardization (ISO) [40,41] to ensure that precise conclusions were obtained. In general, there are four phases of LCA, beginning with goal and scope definition, inventory analysis, life cycle impact assessment, and lastly, interpretation. In the present study, SimaPro software version 8.0 (Pre Consultants 2014) was used with the characterization model of CML 2 baseline 2000 v2.05. The selection of the suitable method for impact estimation was made based on the comparison between the present study and those previously reported, particularly on LCA of bioethanol production [40,42].

2.2.1. Scope of Study and Functional Unit

The objective of the present study was to measure the potential environmental burdens of bioethanol production from the OPF petiole sugar juice. In order to facilitate the LCA and hence identification of the hotspot, each process or step involved in converting the OPF petiole sugar juice into the bioethanol were individually evaluated. Figure 3 shows the schematic diagram of the life cycle of bioethanol produced from OPF petioles and the system boundaries involved. The scope covered the collection of the OPF petioles at the plantation, prior to its transportation to the mill where milling process took place to produce the OPF petiole juice and OPF pressed fiber. Only the juice was utilized for ethanol production, whereas the OPF pressed fiber will be sold as a biomass feedstock to the other party. Concentrated sugar juice was then transported to the biorefinery facility where its fermentation was performed, followed by product purification to attain anhydrous bioethanol (gate-to-gate). All impact was calculated based on a functional unit of 1 tonne of anhydrous bioethanol produced.

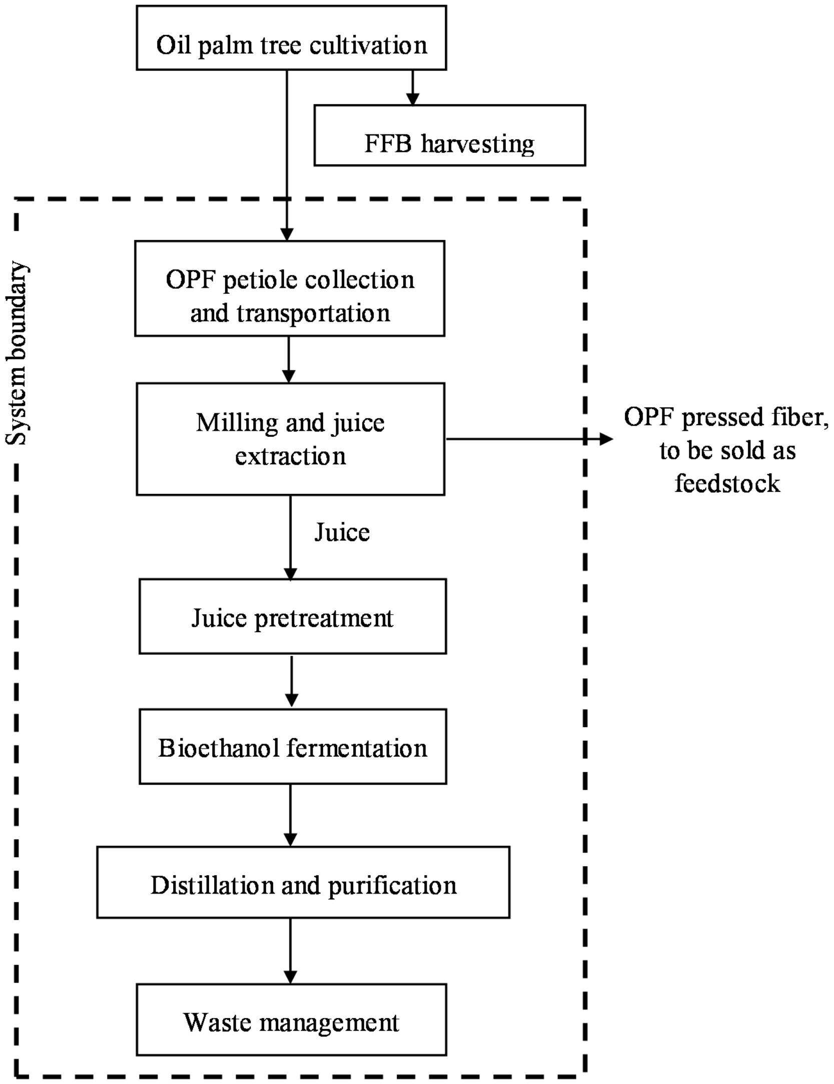

Figure 3. System boundaries for the life cycle assessment of bioethanol production from OPF petiole sugar juice.

2.2.2. Inventory Analysis

Material and energy inputs involved in each process, as well as emissions were calculated and included in the Life Cycle Inventory, which was developed based on ISO 14041. Table 3 shows the data related to transportation, input, output, and emissions during the bioethanol production process. The whole process was categorized into three divisions; OPF collection and transportation, sugar production, and bioethanol production. Since it was proposed that the frond to be conveyed together with the fresh fruit bunches, values on the collection and transportation of OPF petioles was measured based on the fresh fruit bunch harvesting activity conducted at Pusat Penyelidikan Tun Razak, Pahang, while figures on material input and output for sugar production, and upstream and downstream processes for bioethanol production was calculated based on previously reported studies [9,12,15]. The bioconversion of sugars into ethanol through fermentation and its subsequent purification was simulated using Superpro software version 9.5.

Table 3. Inventory data for bioethanol production from OPF petiole sugar juice.

	Values	References
Transportation		
Input		
Trucks, 6 tonne capacity, tkm/year	720,000	This study
Trucks, 20 tonne capacity, tkm/year	504,000	This study
Bioethanol production		
Input		
OPF petiole, tonne/year	230,400	[9]
OPF juice, tonne/year	115,200	[9]
OPF petiole sugars, tonne/year	8400	[9]
Urea, tonne/year	193	This study
Air, tonne/year	168,401	This study
River water, tonne/year	83,927	This study
Output		
OPF pressed fiber, tonne/year	115,200	[9]
Bioethanol, tonne/year	4000	This study
Methane, m^3/year	894,913	This study
Emissions		
CO_2, tonne/year	4074	This study
N_2, tonne/year	129,266	This study
O_2, tonne/year	39,243	This study
Stillage, tonne/year	78,766	This study
Water for recycle, tonne/year	57,600	[9]

2.2.3. Assumptions

Few assumptions were adopted in the present study. Steam and electricity required to run the bioethanol biorefinery were assumed to be solely provided by the oil palm mill, through a cogeneration system using biomass fiber and shell obtained after oil extraction. For the annual mill capacity of 240,000 tonnes/year of FFB processing, 299,325 tonne of high pressure steam at 20 bars can be generated, producing 7.72 GWh of electricity based on boiler and steam efficiency of 77.4% [9]. Only 4.08 GWh of electricity and 510 kg steam per tonne FFB was required for FFB processing, leaving a surplus energy of 3.64 of electricity and 176,925 tonnes/year of steam. On the other hand, total energy requirement for bioethanol production from OPF petiole sugar juice was 1.02 GWh of electricity and 22,689 tonnes of steam (Table 2), which can be supported using the surplus energy from the mill. Since the energy required for operating the biorefinery was obtained from the cogeneration system of the mill, hence, the impact from the energy production by the biorefinery operation was considered negligible, and the amount of energy used was excluded from the inventory. Apart from that, it was also assumed that the wastewater or stillage from the ethanol production line, which includes yeast residue and other solids were channeled to the existing anaerobic wastewater treatment system at the mill for biogas production [30,33,43].

2.2.4. Characterization Model and Impact Categories

CML 2 baseline 2000 incorporated in software SimaPro version 8.0 was employed to perform the Life Cycle Impact Assessment. Ten impact categories were evaluated including abiotic resources depletion (ADP), acidification (AP), eutrophication (EP), global warming (GWP_{100}), ozone layer depletion (ODP), human toxicity (HTP), fresh water ecotoxicity (FETP), marine ecotoxicity (METP), terrestrial ecotoxicity (TETP), and photochemical-oxidant creation potential (POCP). These impact categories were further explained in Section 3.

3. Results and Discussion

Life Cycle Impact Assessment

To recognize the contribution of environmental burdens from the ethanol conversion process, the whole process was fragmented into five sub-processes: transportation, milling and juice extraction, juice treatment, fermentation, and ethanol purification. By comparing the contribution of each sub-process to the environmental burden, the process that required improvement could be identified. Based on the primary, simulation, and literature data, each sub-process was estimated to produce the following products:

- Transportation: 236,700 tonnes of OPF petioles and sugars;
- Milling: 115,200 tonnes of OPF pressed fiber;
- OPF juice extraction: 115,200 tonnes of OPF juice;
- OPF juice treatment: 57,600 tonnes of OPF juice;
- Fermentation: 3984 tonnes of bioethanol;
- Bioethanol purification: 3971 tonnes of bioethanol.

Figure 4 shows the contribution of different bioethanol production stages to the percentage of overall impact for each category, whereas Table 4 lists the Life Cycle Impact Assessment (LCIA) results for each impact category. From Figure 4, it is clear that fermentation had the greatest impact on all categories, ranging from 52% for ODP up to 97% for TETP. This is due to the utilization of urea as the nitrogen source during the process, which has also been reported to associate with high greenhouse gas (GHG) emission, energy consumption, and leaching of nitrates to groundwater [5].

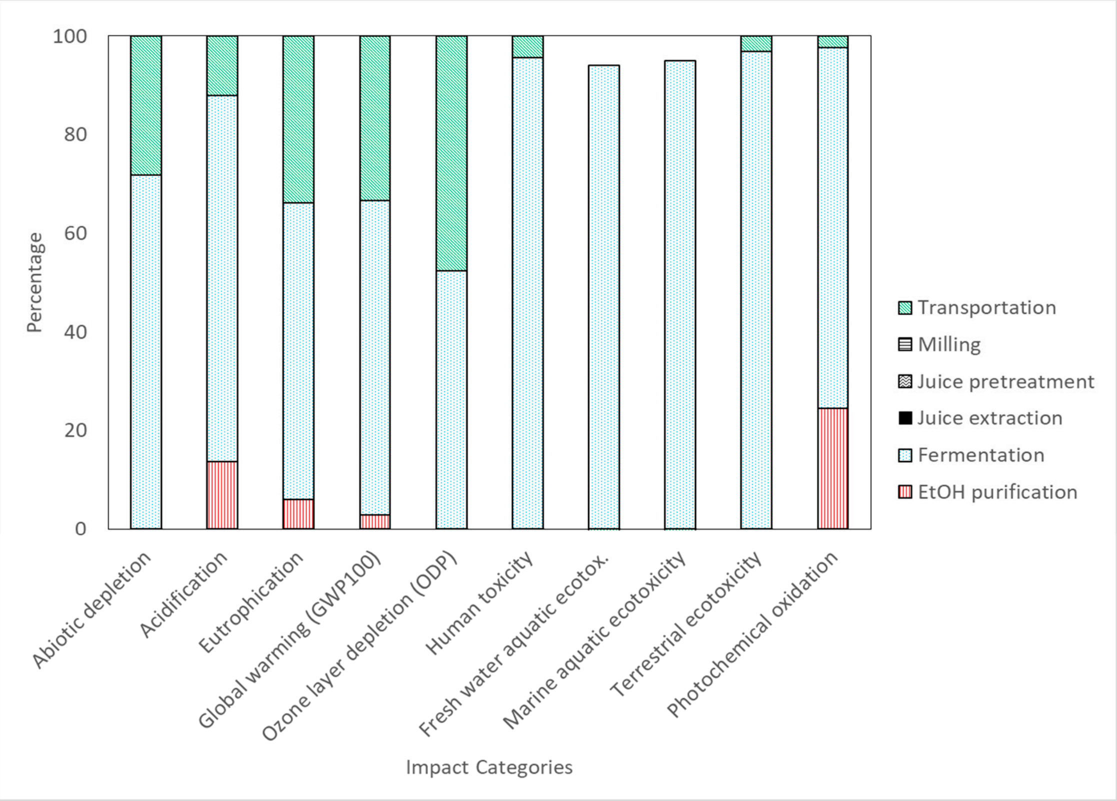

Figure 4. Life cycle impact assessment results for all impact categories per 1 tonne of bioethanol using CML 2 baseline 2000.

Table 4. Environmental impact for all categories assessed by CML 2 2000, for every 1 tonne of bioethanol produced.

Impact Category	Unit	Ethanol Purification	Fermentation	Juice Extraction	Juice Pretreatment	Milling	Transportation
Abiotic depletion	kg Sb eq	5.30E-03	1.29E+00	0.00E+00	0.00E+00	0.00E+00	5.08E-01
Acidification	kg SO_2 eq	1.83E-01	9.89E-01	0.00E+00	0.00E+00	0.00E+00	1.61E-01
Eutrophication	kg PO_4 eq	9.53E-03	9.37E-02	0.00E+00	0.00E+00	0.00E+00	5.29E-02
Global warming (GWP100)	kg CO_2 eq	6.38E+00	1.43E+02	0.00E+00	0.00E+00	0.00E+00	7.46E+01
Ozone layer depletion	kg CFC–11 eq	5.00E-08	6.00E-06	0.00E+00	0.00E+00	0.00E+00	5.50E-06
Human toxicity	kg 1,4–DB eq	1.28E-01	5.78E+01	0.00E+00	0.00E+00	0.00E+00	2.61E+00
Fresh water aquatic ecotoxicity.	kg 1,4–DB eq	3.50E-03	6.47E+00	0.00E+00	0.00E+00	0.00E+00	-4.07E-01
Marine aquatic ecotoxicity	kg 1,4–DB eq	8.49E+00	3.49E+04	0.00E+00	0.00E+00	0.00E+00	-1.84E+03
Terrestrial ecotoxicity	kg 1,4–DB eq	2.83E-04	1.28E+00	0.00E+00	0.00E+00	0.00E+00	4.10E-02
Photochemical oxidation	kg C_2H_4 eq	1.28E-02	3.83E-02	0.00E+00	0.00E+00	0.00E+00	1.21E-03

ADP is denoting to the reduction of mineral, crude oil, or other non-living natural resources, and commonly used to signify the consumption of fossil fuel energy [40]. The unit is kg Sb equivalent. From Table 4, it is apparent that among all processes, fermentation was the dominant contributor (72%) for ADP while 28% was contributed by transportation. High energy utilization during the production of urea contributed to high ADP values for fermentation process whereas in the case of transportation, it was caused by diesel consumption.

Global warming potential was measured by an equal amount of CO_2 emitted to the atmospheres. The energy and resource usage during product generation would directly contribute to atmospheric releases such as CO_2 [2,24], which explains the reason for high impact from fermentation in this category, followed by transportation. Furthermore, according to Kemppainen and Shonnard [44], the climate-active CO_2 is primarily due to the pre-manufacturing life cycle stages of chemicals used in the process. Meanwhile, AP reflected the environmental destruction caused by acidic gas such as sulfur dioxide (SO_2). SO_2 reacts with water in the atmosphere to form acidic rain via a process called acid deposition, which causes ecosystem impairment upon raining [45]. Table 4 also demonstrates that fermentation and ethanol purification gave the most impact on acidic potential with 0.99 and 0.18 kg SO_2 equivalent, respectively, for every 1 tonne of bioethanol produced. According to Wang et al. [40], SO_2 emissions can also be generated from fossil fuel consumption. Therefore, high usage of fossil fuel explained the reason for fermentation contribution in this impact category. Stillage generated from distillation consisted of pollutants including soluble fermentation residues, which led to a pronounced impact in acidification.

Extreme discharge of nitrogen and phosphorus compound (nutrient) into the river and lakes caused a significant impact in the EP. The adverse effect of eutrophication includes changes in species composition and excessive growth of algae, which consequently increase the oxygen degradation process [40,46]. The addition of nitrogen source in the form of urea contributes to nutrient emission, which explained the significant impact from fermentation process. High eutrophication effect was observed due to NH_3 and NO_x emissions from nitrogen-based fertilizer production and application, and diesel use in agricultural machinery and tractors [24].

ODP refers to the reduction in the amount of ozone in the stratosphere due to emission of numerous compounds such as chlorine and bromate [40,46]. It was found that the order of impact associated in this category followed a similar pattern, with fermentation being the major contributor. On the other hand, POCP is associated with the photochemical oxidation or summer smog, occurs due to reactions between NO_x and hydrocarbons or volatile organic compounds (VOC) [40]. Impact arising from fermentation and ethanol purification process was due to emissions from fossil fuel consumption. In the previous studies, it was found that the coal burning for steam and electricity production in bioethanol conversion unit released gas toxin particularly SO_2, resulting in a major impact in POCP [25,46]. In addition, diffused emissions of ethanol from the conversion process also contributed to increased photochemical oxidant [24]. HTP, FAETP, MAETP, and TETP are a group of impact categories that covers the toxic effects from carcinogenic substances or other adverse effects related to human health and the wellbeing of fresh aquatic ecology, marine aquatic ecology, and terrestrial ecosystem [46]. In this case, coal burning was identified as the main source since it yielded high heavy metals such as As, Hg, Pb, and Cr [46]. Extreme utilization of coal for power generation during urea production explains the high ecotoxicity impact coming from fermentation process (Table 4).

Environmental performance of first and second generation bioethanol productions have been previously reported [4,5,22]. By using the LCA approach, the environmental impacts of both cases could be identified and the process sustainability could be improved prior to upscaling. First generation bioethanol refers to the conversion of sugars directly from its source, which is mostly food and involves land clearing and plant cultivation [4]. This results in several problems including direct competition with land use for agriculture as well as damage to the ecosystem [5]. Unlike first generation bioethanol production, second generation bioethanol uses forestry and agricultural residue thus removing issues associated with feedstock cultivation. However, pretreatment and enzymatic hydrolysis were necessary to convert the complex lignocellulosic structure into simple sugar prior to ethanol fermentation [24,47,48]. Most LCA studies identified that pretreatment and enzymatic hydrolysis were the main hotspots due to high energy or fossil fuel consumption for the process and manufacturing of enzyme and chemicals used in the process [5,25,40]. It was estimated that 30% of overall fossil fuel input for ethanol production were contributed by enzymes and chemicals input, thus leading to a high GHG emission such as CO_2 and methane. Nonetheless, lignocellulosic ethanol was reported to offer a lower fossil energy consumption as compared to the first generation ethanol [5].

Hence, the bioethanol production from OPF petiole juice presented in this work is considerably potential for application at the oil palm mill. The conversion of agricultural residue into value-added products not only helps to reduce associated environmental problems, but also eliminates the requirement of land and fertilizer for feedstock cultivation. Furthermore, it only involves simple pressing method to obtain the simple sugars thus avoiding the huge environmental impact arising from pretreatment and enzyme and chemicals application during enzymatic hydrolysis, as previously discussed.

4. Conclusions

An oil palm biomass biorefinery approach for the production of bioethanol from OPF sugar juice was introduced in the present study, followed by an evaluation of the possible impacts coming from the execution of this conceptual model. Based on the energy requirement analysis, it was demonstrated that integration of bioethanol biorefinery at the existing palm oil mill was possible. A gate-to-gate analysis revealed that conversion of OPF petiole juice to bioethanol could potentially generate high negative impacts to all the evaluated categories. Fermentation and transportation were among the main contributors to fossil energy consumption due to urea productions and diesel usage. However, the model proposed in the present study is promising as it eliminates the requirement of highly polluting agricultural stage and pretreatment, and saccharification processes that were required in bioethanol production system utilizing sugars from lignocellulosic fibers. Apart from that, the generation of OPF pressed fiber as a profitable commodity as well as methane gas production from stillage as an additional fuel source helps to improve the overall operational cost of the biorefinery. It is henceforth suggested that a feasibility study on the bioethanol production from OPF sugar juice via integrated biorefinery model to be conducted in the future to demonstrate the process economic of this model.

Author Contributions: Conceptualization, M.A.H. and Y.S.; methodology, S.J.H.M.Y., M.A.H., Y.S. and A.M.R.; software, K.N.I. and S.J.H.M.Y.; validation, S.J.H.M.Y., A.M.R., K.N.I., S.S.S.A., M.R.Z., M.A.H., and Y.S.; formal analysis, S.J.H.M.Y. and A.M.R.; investigation, S.J.H.M.Y.; resources, M.A.H. and Y.S.; data curation, S.J.H.M.Y., K.N.I. and A.M.R.; Writing—Original draft preparation, S.J.H.M.Y.; Writing—Review and editing, S.J.H.M.Y., A.M.R. and M.A.H.; visualization, S.J.H.M.Y.; supervision, M.A.H., Y.S. and A.M.R.; project administration, M.A.H.; funding acquisition, M.A.H. and Y.S.

Funding: This research was funded by Japan Science and Technology Agency (JST) and Japan International Cooperation Agency (JICA), grant name Science and Technology Research Partnership for Sustainable Development (SATREPS).

Acknowledgments: The authors wish to acknowledge Universiti Putra Malaysia and Universiti Kuala Lumpur for providing the facilities and access to the SimaPro software used in this study. Appreciation also goes to Universiti Malaysia Perlis and the Ministry of Higher Education, Malaysia for the provision of study leave and scholarship for the first author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. U.S. Energy Information Administration. *International Energy Outlook 2017*; Energy Information Administration: Washington, DC, USA, 2017; pp. 1–151.
2. Roy, P.; Orikasa, T.; Tokuyasu, K.; Nakamura, N.; Shiina, T. Evaluation of the life cycle of bioethanol produced from rice straws. *Bioresour. Technol.* **2012**, *110*, 239–244. [CrossRef] [PubMed]
3. US Energy Information Administration. *International Energy Outlook 2016*; Chapter 1: World Energy Demand and Economic Outlook 2016; Energy Information Administration: Washington, DC, USA, 2016; pp. 7–17.
4. Morales, M.; Quintero, J.; Conejeros, R.; Aroca, G. Life cycle assessment of lignocellulosic bioethanol: Environmental impacts and energy balance. *Renew. Sustain. Energy Rev.* **2015**, *42*, 1349–1361. [CrossRef]
5. Borrion, A.L.; McManus, M.C.; Hammond, G.P. Environmental life cycle assessment of lignocellulosic conversion to ethanol: A review. *Renew. Sustain. Energy Rev.* **2012**, *16*, 4638–4650. [CrossRef]
6. Pourbafrani, M.; MacLean, H.L.; McKechnie, J.; Saville, B.A. Life cycle greenhouse gas impacts of ethanol, biomethane and limonene production from citrus waste. *Environ. Res. Lett.* **2013**, *8*, 015007. [CrossRef]
7. Loh, S.K. The potential of the Malaysian oil palm biomass as a renewable energy source. *Energy Convers. Manag.* **2017**, *141*, 285–298. [CrossRef]
8. Lee, K.T.; Ofori-Boateng, C. *Sustainability of Biofuel Production from Oil Palm Biomass*; Springer Science and Business Media LLC: Berlin, Germany, 2013.
9. Abdullah, S.S.S.; Shirai, Y.; Ali, A.A.M.; Mustapha, M.; Hassan, M.A. Case study: Preliminary assessment of integrated palm biomass biorefinery for bioethanol production utilizing non-food sugars from oil palm frond petiole. *Energy Convers. Manag.* **2016**, *108*, 233–242. [CrossRef]
10. Ofori-Boateng, C.; Lee, K.T. Sono-assisted organosolv/H_2O_2 pretreatment of oil palm (*Elaeis guineensis Jacq.*) fronds for recovery of fermentable sugars: Optimization and severity evaluation. *Fuel* **2014**, *115*, 170–178. [CrossRef]
11. Lee, K.T.; Ofori-Boateng, C. *Advances in Biofuels*; Pogaku, R., Sarbatly, R.H., Eds.; Springer: New York, NY, USA, 2013.
12. Zahari, M.A.K.M.; Ariffin, H.; Mokhtar, M.N.; Salihon, J.; Shirai, Y.; Hassan, M.A. Case study for a palm biomass biorefinery utilizing renewable non-food sugars from oil palm frond for the production of poly(3-hydroxybutyrate) bioplastic. *J. Clean. Prod.* **2015**, *87*, 284–290. [CrossRef]
13. Abdullah, S.S.S.; Shirai, Y.; Bahrin, E.K.; Hassan, M.A. Fresh oil palm frond juice as a renewable, non-food, non-cellulosic and complete medium for direct bioethanol production. *Ind. Crop. Prod.* **2015**, *63*, 357–361. [CrossRef]
14. Zahari, M.A.K.M.; Abdullah, S.S.S.; Roslan, A.M.; Ariffin, H.; Shirai, Y.; Hassan, M.A. Efficient utilization of oil palm frond for bio-based products and biorefinery. *J. Clean. Prod.* **2014**, *65*, 252–260. [CrossRef]
15. Zahari, M.A.K.M.; Zakaria, M.R.; Ariffin, H.; Mokhtar, M.N.; Salihon, J.; Shirai, Y.; Hassan, M.A. Renewable sugars from oil palm frond juice as an alternative novel fermentation feedstock for value-added products. *Bioresour. Technol.* **2012**, *110*, 566–571. [CrossRef] [PubMed]
16. Goh, C.S.; Tan, H.T.; Lee, K.T. Pretreatment of oil palm frond using hot compressed water: An evaluation of compositional changes and pulp digestibility using severity factors. *Bioresour. Technol.* **2012**, *110*, 662–669. [CrossRef] [PubMed]
17. Zakaria, M.R.; Fujimoto, S.; Hirata, S.; Hassan, M.A. Ball Milling Pretreatment of Oil Palm Biomass for Enhancing Enzymatic Hydrolysis. *Appl. Biochem. Biotechnol.* **2014**, *173*, 1778–1789. [CrossRef] [PubMed]
18. Zakaria, M.R.; Hirata, S.; Hassan, M.A. Hydrothermal pretreatment enhanced enzymatic hydrolysis and glucose production from oil palm biomass. *Bioresour. Technol.* **2015**, *176*, 142–148. [CrossRef]

19. Sabiha-Hanim, S.; Noor, M.A.M.; Rosma, A. Effect of autohydrolysis and enzymatic treatment on oil palm (*Elaeis guineensis Jacq.*) frond fibres for xylose and xylooligosaccharides production. *Bioresour. Technol.* **2011**, *102*, 1234–1239. [CrossRef]
20. Scown, C.D.; Nazaroff, W.W.; Mishra, U.; Strogen, B.; Lobscheid, A.B.; Masanet, E.; Santero, N.J.; Horvath, A.; Mckone, T.E. Corrigendum: Lifecycle greenhouse gas implications of US national scenarios for cellulosic ethanol production. *Environ. Res. Lett.* **2012**, *7*, 019502. [CrossRef]
21. Ometto, A.R.; Hauschild, M.Z.; Roma, W.N.L. Lifecycle assessment of fuel ethanol from sugarcane in Brazil. *Int. J. Life Cycle Assess.* **2009**, *14*, 236–247. [CrossRef]
22. Muñoz, I.; Flury, K.; Jungbluth, N.; Rigarlsford, G.I.; Canals, L.M.; King, H. Life cycle assessment of bio-based ethanol produced from different agricultural feedstocks. *Int. J. Life Cycle Assess.* **2014**, *19*, 109–119. [CrossRef]
23. Wang, M.; Han, J.; Dunn, J.B.; Cai, H.; Elgowainy, A. Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use. *Environ. Res. Lett.* **2012**, *7*, 045905. [CrossRef]
24. Borrion, A.L.; McManus, M.C.; Hammond, G.P. Environmental life cycle assessment of bioethanol production from wheat straw. *Biomass Bioenergy* **2012**, *47*, 9–19. [CrossRef]
25. Wang, L.; Littlewood, J.; Murphy, R.J. An economic and environmental evaluation for bamboo-derived bioethanol. *RSC Adv.* **2014**, *4*, 29604–29611. [CrossRef]
26. Roslan, A.M. Oil Palm Frond Petiole Conversion into Biosugars and Bioethanol. Ph.D. Thesis, Kyushu Institute of Technology, Kitakyushu, Japan, 2014.
27. Roslan, A.M.; Zahari, M.A.K.M.; Hassan, M.A.; Shirai, Y. Investigation of oil palm frond properties for use as biomaterials and biofuels. *Trop. Agric. Dev.* **2014**, *58*, 26–29.
28. Dias, M.O.; Ensinas, A.V.; Nebra, S.A.; Filho, R.M.; Rossell, C.E.; Maciel, M.R.W. Production of bioethanol and other bio-based materials from sugarcane bagasse: Integration to conventional bioethanol production process. *Chem. Eng. Res. Des.* **2009**, *87*, 1206–1216. [CrossRef]
29. Reis, C.E.R.; Hu, B. Vinasse from sugarcane ethanol production: Better treatment or better utilization? *Front. Energ. Res.* **2017**, *5*, 1–17.
30. Wilkie, A.C.; Riedesel, K.J.; Owens, J.M. Stillage characterization and anaerobic treatment of ethanol stillage from conventional and cellulosic feedstocks. *Biomass Bioenergy* **2000**, *19*, 63–102. [CrossRef]
31. Sebastião, D.; Gonçalves, M.S.; Marques, S.; Fonseca, C.; Gírio, F.; Oliveira, A.C.; Matos, C.T. Life cycle assessment of advanced bioethanol production from pulp and paper sludge. *Bioresour. Technol.* **2016**, *208*, 100–109. [CrossRef]
32. Krzywonos, M.; Cibis, E.; Miskiewicz, T.; Ryznar-Luty, A. Utilization and biodegradation of starch stillage (distillery wastewater). *Electron. J. Biotechnol.* **2009**, *12*, 1–12. [CrossRef]
33. Kaparaju, P.; Serrano, M.; Angelidaki, I. Optimization of biogas production from wheat straw stillage in UASB reactor. *Appl. Energy* **2010**, *87*, 3779–3783. [CrossRef]
34. Parsaee, M.; Kiani, M.K.D.; Karimi, K. A review of biogas production from sugarcane vinasse. *Biomass Bioenergy* **2019**, *122*, 117–125. [CrossRef]
35. Tian, Z.; Mohan, G.R.; Ingram, L.; Pullammanappallil, P. Anaerobic digestion for treatment of stillage from cellulosic bioethanol production. *Bioresour. Technol.* **2013**, *144*, 387–395. [CrossRef]
36. Nasrin, A.; Ravi, N.; Lim, W.; Choo, Y.; Fadzil, A. Assessment of the performance and potential export renewable energy (RE) from typical cogeneration plants used in palm oil mills. *J. Eng. Appl. Sci.* **2011**, *6*, 433–439.
37. Yoshizaki, T.; Shirai, Y.; Hassan, M.A.; Baharuddin, A.S.; Abdullah, N.M.R.; Sulaiman, A.; Busu, Z. Improved economic viability of integrated biogas energy and compost production for sustainable palm oil mill management. *J. Clean. Prod.* **2013**, *44*, 1–7. [CrossRef]
38. Ensinas, A.V.; Nebra, S.A.; Lozano, M.A.; Serra, L.M. Analysis of process steam demand reduction and electricity generation in sugar and ethanol production from sugarcane. *Energy Convers. Manag.* **2007**, *48*, 2978–2987. [CrossRef]
39. Renó, M.L.G.; Almazán del Olmo, O.A.; Palacio, J.C.E.; Lora, E.E.S.; Venturini, O.J. Sugarcane biorefineries: Case studies applied to the Brazilian sugar—Alcohol industry. *Energy Convers. Manag.* **2014**, *86*, 981–991.
40. Wang, L.; Littlewood, J.; Murphy, R.J. Environmental sustainability of bioethanol production from wheat straw in the UK. *Renew. Sustain. Energy Rev.* **2013**, *28*, 715–725. [CrossRef]
41. Chau, C.-K.; Leung, T.; Ng, W. A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings. *Appl. Energy* **2015**, *143*, 395–413. [CrossRef]

42. Chiew, Y.L.; Shimada, S. Current state and environmental impact assessment for utilizing oil palm empty fruit bunches for fuel, fiber and fertilizer—A case study of Malaysia. *Biomass Bioenergy* **2013**, *51*, 109–124. [CrossRef]
43. Kaparaju, P.; Serrano, M.; Thomsen, A.B.; Kongjan, P.; Angelidaki, I. Bioethanol, biohydrogen and biogas production from wheat straw in a biorefinery concept. *Bioresour. Technol.* **2009**, *100*, 2562–2568. [CrossRef]
44. Kemppainen, A.J.; Shonnard, D. Life cycle assessments for biomass-to-ethanol production from different regional feedstock. *Biotechnol. Prog.* **2005**, *21*, 1075–1084. [CrossRef]
45. Prasad, A.; Sotenko, M.; Blenkinsopp, T.; Coles, S.R. Life cycle assessment of lignocellulosic biomass pretreatment methods in biofuel production. *Int. J. Life Cycle Assess.* **2016**, *21*, 44–50. [CrossRef]
46. Wang, M.; Chen, Y.; Xia, X.; Li, J.; Liu, J. Energy efficiency and environmental performance of bioethanol production from sweet sorghum stem based on life cycle analysis. *Bioresour. Technol.* **2014**, *163*, 74–81. [CrossRef] [PubMed]
47. Alvira, P.; Tomás-Pejó, E.; Ballesteros, M.; Negro, M.J. Pretreatment technologies for an efficient bioethanol production process based on enzymatic hydrolysis: A review. *Bioresour. Technol.* **2010**, *101*, 4851–4861. [CrossRef] [PubMed]
48. Bensah, E.C.; Mensah, M. Chemical Pretreatment Methods for the Production of Cellulosic Ethanol: Technologies and Innovations. *Int. J. Chem. Eng.* **2013**, *2013*, 1–21. [CrossRef]

© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).