RENEWABLE ENERGY PRODUCTION FROM PALM BIOMASS BY PYROLYSIS: A PATH TO ACHIEVE ECONOMIC AND ENVIRONMENTAL SUSTAINABILITY

Shahidul, M.I.
Faculty of Engineering, Universiti Malaysia Sarawak, 94300, Kota Samarahan, Sarawak, Malaysia
Email: mislam@unimas.my, shahid.buet1986@gmail.com

ABSTRACT: *This study aims to unlock the information on the renewable energy production performance from carbon emission potential waste palm biomass. The specific objective of this paper is to reveal the current advancement in the pyrolysis process and its ability to replace fossil fuel with palm biomass. This study also addresses the problem relating to carbon emissions from waste palm biomass for contributing to achieving economic and environmental sustainability in Southeast Asian countries. The research methodology used for this study is reviewing the published research papers. The number of reviewed journals was 75 and published between 2010 to 2022 on research findings relating to the aims of this study. The study revealed that advancements in the pyrolysis process have significantly contributed to producing renewable energy from palm biomass. The temperature range of palm biomass pyrolysis is from 300OC to 9000 C. Energy products of this process are bio-oil, syngas, hydrogen, and bio-char. The energy output of this process is about 17.5MJ per kg of palm biomass. Combined heat and power cycle installed in series with palm biomass pyrolysis for achieving energy production efficiency up to 95%. Palm biomass pyrolysis offers a few benefits. It contributes to substituting fossil fuels with renewable energy and reducing 0.75kg CO_2eq emission. The research outcomes listed in this paper would be a guideline for investors, policymakers, researchers, government agencies, and industries for making a strategic plan to implement palm biomass-based renewable energy production plants. The novelty of this study is a presentation of ways to convert waste palm biomass into renewable energy with advanced technology.*

Keywords: Palm Biomass, Advanced Technology, Clean Energy, Production Performance, Optimization, Economic Sustainability, Environmental Sustainability, Climate Change.

1.0 BACKGROUND OF THE STUDY

In 2020, the global Fresh Fruit Bunches (FFB) production was about 220 million tons [1, 2]. The average rate of crude palm oil (CPO) outputs from FEB was 22%, and the other 78% was waste [3–5]. The waste part is known as Empty Fruit Bunch (EFB); and it is a biomass. EFB has traditionally been dumped into the environment. A small part of this biomass is also used for producing steam and energy.

When EFB degrades in the atmosphere, this biomass emits The carbon [CO_2eq(methane-CH_4) and carbon dioxide-CO_2)] [6]. and carbon emission potential is about 60kgCO_2eq.$(ton)^{-1}$ [7]. When EFB burns for steam and energy, the emission rate is about 29CO_2eq.$(kWh)^{-1}$. In both ways, EFB is environmentally hazardous biomass. On the other hand, dry EFB contains Carbon (45.53 wt. %) and hydrogen(5.46 wt.%), which represent energy[8]. his energy is environmentally friendly and renewable [9, 10].

With this background, the current study has undertaken to answer whether "***is waste palm biomass a renewable green energy source****?"* This study conducts to find the answer to this question. Total 75 journal papers studied published between 2010 and 2022 related to this question.

This paper divides into 5 sections. Energy contents of palm biomass describe in section 2. Section 3 gives an overview of advancements in technology relating to energy production from waste palm biomass. Section 4 describes the economic and environmental benefits of producing renewable energy from waste palm biomass. Section 5 is for conclusion and recommendation.

2.0 ENERGY POTENTIAL OF PALM BIOMASS

The earth receives around 1000 W.$(m)^{-2}$ of power from the Sun and only a fraction of this solar energy can convert into biomass (chemical energy) via the process of photosynthesis with water, and carbon dioxide. Palm biomass is also growing by absorbing solar energy, water and carbon dioxide. Equation 1.0 presents the formation of biomass.

$$Es + CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2 \qquad \text{Eq (1)}$$

Here, Es is the solar energy, and $C_6H_{12}O_6$ is biomass, and a renewable organic material [11, 12]. Table 1 presents the specific heat capacity of Palm biomass.

Table 1: Specific Heat Capacity of Palm Biomass

Type of Biomass	Cpi (kJ/kg·K)	Type of Biomass	Cpi (kJ/kg·K)
FFB	3.231 [13]	MF	2.816 [13]
EFB	1.483 [14]	PKS	2.083 [15]
Nuts and Shells	2.291 [13]	OPT	2.567 [13]

The calorific value of FFB is comparable to the low-rank coal. The energy contents of EFB depend on moisture level. Palm biomass is highly volatile, and suitable for liquid fuel production. The calorific value of palm residues varies between 18 to 21 MJ. $(kg)^{-1}$. Palm kernel shell (PKS) and Mesocarp fiber (MF) have used in the boilers to generate steam [8], [16]. The Table 2 presents the energy contents of EFB.

Table 2: Energy Content in EFB [17], [18]

Type of Biomass	Energy and Physical Properties			
	Gross Calorific Value (MJ kg^{-1})	Moisture Content (wt.%)	Ash Content (wt.%)	Volatile Matter Content (wt.%)
EFB	38.3	35.3	22.1	2.7
MF	33.9	26.1	27.7	6.9
PKS	20.8	22.7	50.7	4.8
OPF	30.4	40.4	21.7	1.7
OPT	34.5	31.8	25.7	3.7

The energy value per kg of EFB increases with the moisture reduction rate. For example, the calorific value or low heating value (LHV) of palm biomass is about 15.0 MJ. $(kg)^{-1}$ at moisture level 50%. The HHV is 17.17MJ. $(kg)^{-1}$

when dry at 220 °C (moisture about 30%). The HHV is 17.67 MJ. $(kg)^{-1}$ when dry at 250 °C for moisture level 20%) [19, 20].

Palm biomass is an environmentally friendly fuel compared to the fossil fuel. The LHV of palm biomass is about 15.0 MJ.$(kg)^{-1}$ with 0.24 $kgCO_2eq$ emission at 20% moisture [16]. On the other hand, the LHV of coal is 32.56 MJ.$(Kg)^{-1}$ with a 1.20 $kgCO_2eq$ emission [16, 21]. In this aspect of the environment, the EFB is a better choice as a solid fuel compared to coal. However, palm biomass can convert into the renewable energy in the form of heat, gaseous fuels, and electricity through various processes [22, 23].

3.0 TECHNOLOGICAL ADVANCEMENT IN ENERGY PRODUCTION FROM PALM BIOMASS

Technology and process machinery require to produce energy from palm biomass [24]. Organic Rankine Cycle (ORC) is the most common thermal process used for energy production from this biomass [25]. Pre-treatment for palm biomass is the first step in energy production. The second step is feedstock (pellet) preparation. The final step is energy production by using gasification or pyrolysis with CHP [26]. The range of energy yield from palm biomass is from 60% to over 90% [16] depending on technology used in energy production [21].

3.1 Feedstock Preparation for Energy Production from Palm Biomass

Energy production performance from palm biomass depends on feedstock quality and technology use. Three steps involve in feedstock preparation from palm biomass. The steps are pre-treatment with an alkaline solution (NaOH), removing moisture, and Pellet preparation [27]. Pre-treatment of palm biomass speed up breaking the long chain of lignin to a short chain and increases the cell surface area [28, 29]. In the second stage, palm biomass dries to reduce moisture. Pellets production is the final stage [26].

3.2 Pyrolysis Process for Energy Production from Palm

Pyrolysis is an endothermic process that requires thermal energy from an external source [30]**.** This process performs in the absence of oxygen. Hot air (≥700 °C) and steam supply to the pyrolysis reactor to speed up endothermic reaction [31–34]. Palm biomass pellet feeds to a reactor for decomposing biomass [35, 36]. Figure 1 presents a schematic diagram of palm biomass pyrolysis process.

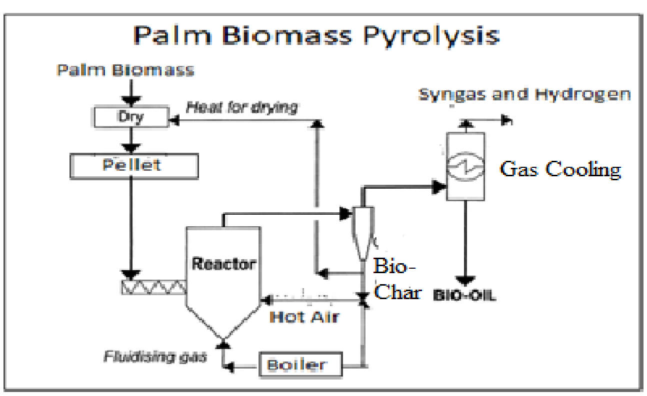

Figure 1: Schematic Diagram of Pyrolysis Process

This process occurs at a higher heat transfer rate, and a process temperature of 300°C to 900 °C. Through the degrading process, palm biomass converts into the vapor. A rapid cooling system uses for condensing the vapor into a liquid fuel [35, 37].The energy products of pyrolysis are bio-oil, biogas, hydrogen, and biochar [38–40]. The pyrolysis with catalysis offers a higher energy yield at a lower process time and energy [41, 42].Table 3.0 presents the energy products of palm biomass pyrolysis.

Table 3: Yields of EFB's Pyrolysis

Pyrolysis Temperature (°C)	Product from Pyrolysis		
	Bio-oil (wt.%)	Syngas (%)	Biochar (%)
300-400	48.5 [5], [43]	15.2	36.5[38][44]
500	56.2 [26], [45]	18.5	25.3
600	40 [46]	29.5	20.10
600-950	<40 [41]	>30	<20

Table 3 demonstrates that at pyrolysis temperature 300^0C to 500^0C, the bio-oil (≈48.5% wt.) and bio-char ((≈36.5.5% wt.) are the dominant products [5, 43, 47]. At pyrolysis temperature more than 500^0C, syngas production increase with temperature; and yield of bio oil and bio-char reduce. The yield of syngas is the highest level ((≥30% wt.) at temperature 900^0C [29, 44]. Table 4 presents the energy value produce from palm biomass pyrolysis.

Table 4: Energy Properties of Palm Biomass [46, 48, 49]

Energy product	Energy value (LHV)
Bio-oil, process temperature ≥300°C	24.90-31.16 MJ $(kg)^{-1}$ [50]
Bio-char, process ≥ 400°C temperature ≥300°C	23-26 MJ $(kg)^{-1}$ [51]
Methane gas ≥750°C	50-55MJ.$(kg)^{-1}$[52].
Hydrogen ≥900°C	120-142MJ.$(Kg)^{-1}$ [52].

The data stated in Table 3 and Table 4 demonstrate that syngas and hydrogen start to produce at temperatures ranging from 430°C to 950°C [52]. At higher temperatures (>750°C), CH_4 gas breaks and converts into hydrogen. The energy production performance of pyrolysis has appeared at an optimum temperature of 950°C, and this process contributes to producing energy at a lower carbon emission rate (CO_2) [30, 53].

The findings stated in this section conclude that pyrolysis is an effective thermal process for producing renewable energy from waste palm biomass; and a sustainable way to reduce carbon emission [CO_2eq.$(kWh)^{-1}$]. In that aspect, the pyrolysis process installation at palm oil mills to produce renewable energy would contribute to achieving SDG 7 and SDG13 [53].

3.3 Combined Heat and Power Cycle in Energy Production from Palm Biomass

The Combined Heat and Power (CHP) cycle uses in pyrolysis processes [54, 55]. The CHP process contributes to achieve thermal efficiency from 60 to 95 percent by utilizing waste heat in renewable energy production [56–58].

There are two purposes of installing CHP in the palm biomass thermal decomposing process. The first objective is the increasing thermal efficacy by capturing waste heat and for recycling. The second objective is the decreasing the carbon emission rate per kW energy [59, 60].Various cases also report that energy production from palm biomass can reduce carbon emission rates [61, 62].

3.3.1 Environmental Benefits of Using CHP Energy Production from Palm Biomass

The CHP offers a few benefits when energy produces from palm biomass. The CHP requires less palm biomass for producing each unit of energy, which contributes to reducing the emissions rate per unit of energy (CO_2eq.$(kWh)^{-1}$ [30]. When energy produces without CHP, the emission rate is 0.15kgCO_2eq.$(kWh)^{-1}$ at a thermal efficiency of 40%. Emission is 0.06kg CO_2eq. $(kWh)^{-1}$ when the plant operates with CHP at a thermal efficiency of 95% [63–65].

3.3.2 Economic Benefits of Using CHP in Energy Production from Palm Biomass

Energy production performance from palm biomass at higher thermal efficiency (≥95%) leads to achieving economic sustainability [66], [67]. CHP process requires about 40% less fuel to produce each unit of energy and reduce energy production cost. If syngas and hydrogen produce simultaneously from palm biomass, the thermal efficiency would be about 95 percent [55, 68], and energy production cost could be less than the fossil fuel [69, 70]. This background demonstrates that energy production from palm biomass with the aid of CHP would contribute to achieving SDG 7, SDG 8, and SDG 13.

4.0 SUMMARY OF FINDINGS

This paper underlines the advancement of technology that has using in producing renewable energy from carbon emission (CO_2eq) potential palm biomass. Pyrolysis with CHP uses to produce energy from palm biomass. The energy product of palm biomass pyrolysis are bio-oil, biogas, and biochar are energy products which are sustainable substitute of fossil fuels. The energy yield (LHV) from this biomass is 15.0 MJ. $(kg)^{-1}$ at moisture 50%. The HHV is 17.17 MJ. $(kg)^{-1}$ when dry at 220 °C, while dry at 250°C, HHV is 17.67 MJ. $(kg)^{-1}$ [71, 72].

4.1 Economic and Environment Benefits

Energy production from waste palm biomass offers two environmental benefits. Firstly, it is a replaceable fuel by fossil fuels that contribute to reducing carbon emissions at the rate of 700kg. $(kWh)^{-1}$ to 1100kg. $(kWh)^{-1}$. The second benefit is 1130kg CO_2eq$(t)^{-1}$ carbon emission reduction from palm biomass [62, 73]. The carbon reduction per unit of energy is 0.76kg $CO_2(MJ)^{-1}$ [74, 75]. In consideration of coal, the estimated energy production and emission balance from palm biomass is -1368g CO_2eq.$(kWh)^{-1}$ [61, 62].

4.2 Challenges and Way Forward

The biggest challenge of using palm biomass for energy production are:

- High moisture (≥50%) contents.
- Lack of skilled human resources for design, set up, and operations of plant machinery
- The technology used in renewable energy production is still young, pilot-scale, and not in a fully mature state.
- Technologies currently available in the market for renewable energy production are capital intensive compared to the fossil fuel power plants.

A comprehensive plan requires to address all these challenges. The findings suggest, require conducting in-depth research to innovate sustainable technology. Southeast Asian countries may take R&D projects to develop the required infrastructure and human resources. Government agencies-Industry-University can work together to find a sustainable solution of these constrains.

4.3 Implication of Findings

The results published in this paper would be a reference for researchers to conduct further studies in this field. The research outcomes would attract government agencies, industries, and policymakers to implement palm biomass-based renewable energy project.

5.0 CONCLUSION AND RECOMMENDATION

A key measure to combat climate change is renewable energy production and use. A significant percentage of emissions can reduce by producing clean energy from palm biomass. These goals can achieve by the Southeast Asian countries by setup R&D facilities aiming to develop the required infrastructure. In addition, the relevant stakeholders shall pay attention to finding ways to develop human resources and technologies.

This study concludes that the clean energy (SDG 7) production from carbon emission (CO_2eq) potential palm biomass may empower Southeast Asian countries to achieve economic (SDG 8) and environmental sustainability (SDG 13).

REFERENCES

[1] L. J. . Lee M.K., Hashim H., Hoo P.Y., Ho W.S., Yunus N.A., "Biogas Generated from Palm Oil Mill Effluent for Rural Electrification and Environmental Sustainability," *Chem. Eng. Trans.*, vol. 61, pp. 1537–1542, 2017.

[2] L. Loh S.K., Nasrin A.B., Mohamad Azri S., Nurul Adela B., Muzammil N., Daryl Jay T., Stassha Elanor R.A. and 2017 W.S., Choo Y.M., Kaltschmitt M., "First Report on Malaysia's Experiences and Development in Biogas Capture and Utilization from Palm Oil Mill Effluent Under the Economic Transformation Programme: Current and Future Perspectives," *Renew. Sustain. Energy Rev.*, vol. 74, pp. 1257–1274, 2017.

[3] A. H. Zamri, M. F. M. A., Akhiar, A., Shamsuddin, "Talking points of green and sustainable palm oil mill system in Malaysia," *Int. J. Recent Technol. Eng.*, vol. 8, no. 8, pp. 6474–6479, 2019.

[4] MPOB statistices, "MPOB -Economic and Industry Development Divisions," 2021. [Online]. Available: https://bepi.mpob.gov.my/index.php/en/production/production-2021/production-of-crude-oil-palm-2021

[5] M. I. Shahidul, M. L. Malcolm, and J. J. Eugene, "Methane Production Potential of POME: A Review on Waste-to-Energy [WtE] Model," *Sci Int*, vol. 30, no. 5, pp. 717–728, 2018.

[6] A. A. M. Ali, M. R. Othman, Y. Shirai, and M. A. Hassan, "Sustainable and integrated palm oil biorefinery concept with value-addition of biomass and zero emission system," *J. Clean. Prod.*, vol. 91, 2015, doi: 10.1016/j.jclepro.2014.12.030.

[7] M. I. Shahidul, B. Shahnur, M. M. Lamoh, M. S. Hashmi, and M. S. Islam, "The Role of Engineering

in Mitigating Global Climate Change Effects: Review of the Aspects of Carbon Emissions from Fossil Fuel-Based Power Plants and Manufacturing Industries," in *Reference Module in Materials Science and Materials Engineering*, Elsevier, 2018. doi: 10.1016/B978-0-12-803581-8.11274-3.

[8] S. B. Uemura, Y.; Omar, W.N.; Tsutsui, T.; Yusup, "Torrefaction of oil palm wastes," *Fuel*, vol. 90, pp. 2585–2591, 2011.

[9] F. Abdullah, N., Gerhauser, H. & Sulaiman, "Fast pyrolysis of empty fruit bunches," *Fuel*, vol. 89, pp. 2166–2169, 2010.

[10] Y.-S. Wong, T. T. Teng, S.-A. Ong, M. Norhashimah, M. Rafatullah, and H.-C. Lee, "Anaerobic Acidogenesis Biodegradation of Palm Oil Mill Effluent Using Suspended Closed Anaerobic Bioreactor (SCABR) at Mesophilic Temperature," *Procedia Environ. Sci.*, vol. 18, pp. 433–441, 2013, doi: 10.1016/j.proenv.2013.04.058.

[11] Infromation, U.S EnergyAdministration, "No Title," 2021. [Online]. Available: https://www.eia.gov/energyexplained/biomass/

[12] D. J.-F. Scarlat N, Martinov M, "Assessment of the availability of agricultural crop residues in the European Union: potential and limitations for bioenergy use," *Waste Manag.*, vol. 30, pp. 1889–1897, 2010.

[13] T. M. S. Ab Hadi A., Mohammad A.W., "Spreadsheet Modelling for Temperature Profile Inside Palm Oil Fresh Fruit Bunch," *J. Ind. Eng. Res.*, vol. 1, no. 6, pp. 25–32, 2015.

[14] T. A. T. . Nyakuma B.B., Johari A. Ahmad A., "Comparative Analysis of the Calorific Fuel Properties of Empty Fruit Bunch Fiber and Briquette," *Int. Conf. Altern. Energy Dev. Ctries. Emerg. Econ.*, vol. 52, pp. 466–473, 2013.

[15] K. O. . Fono-Tamo R.S., "Characterisation of Pulverised Palm Kernel Shell for Sustainable Waste Diversification," *Int. J. Sci. Eng. Res.*, vol. 4, no. 4, pp. 6–10, 2013.

[16] T. and S. B. Y. Yoshimitsu Uemura, Wissam N.Omar, "Torrefaction of oil palm wastes," *Fuel*, vol. 90, no. 8, pp. 2585–2591, 2011.

[17] S. J. Abnisa F, Arami-Niya A, Daud WMAW, "Characterization of Bio-oil and Bio-char from Pyrolysis of Palm Oil Wastes," *BioEnergy Res*, vol. 6, pp. 830–840, 2013, doi: . doi:10.1007/s12155-013-9313-8.

[18] N. B. A. I. K. A. Hamid, "Pyrolysis of empty fruit bunch by thermogravimetric analysis," *Energy Procedia*, vol. 61, pp. 2532–2536, 2014, doi: : 10.1016/j.egypro.2014.12.039.

[19] K. Y. Sirawasith Ruksathamcharoena , Teerapong Chuenyama , Pimpet Stratong-onb , Hideki Hosodab , Tri Sesilliaa, "Effects of hydrothermal treatment and pelletizing temperature on physical properties of empty fruit bunch pellets," *Energy Procedia*, vol. 158, pp. 681–687, 2017.

[20] H. A. and P. V. Anna Brunerová, Miroslav Müller, Vladimír Šleger, "Bio-Pellet Fuel from Oil Palm Empty Fruit Bunches (EFB): Using European Standards for Quality Testing," *Sustainability*, vol. 10, 2018, doi: doi:10.3390/su10124443.

[21] R. F. and P. J. Arias B, Pevida C, Fermoso J, Plaza MG, "Influence of torrefactionon the grindability and reactivity of woody biomass.," *Fuel proecss Technol.*, vol. 89, pp. 169–175, 2008.

[22] Y. Jianga, Edwin van der Werfb, E. C. van Ierlandb, and K. J. Keesmana, "The potential role of waste biomass in the future urban electricity system," *Biomass and Bioenergy*, vol. 107, pp. 182–190, 2017, doi: https://doi.org/10.1016/j.biombioe.2017.10.001.

[23] H. RJ, : "Evaluation of plant biomass resources available for replacement of fossil oil," *Plant Biotechnol J*, vol. 8, pp. 288–293, 2010.

[24] United Nations, "No Biofuel production technologies: status, prospects and implications for trade and development Title," New York, 2008. [Online]. Available: https://unctad.org/system/files/official-document/ditcted200710_en.pdf

[25] M. N. A. Nur, Bin Taufiq, Zulkarnaen Pane, "Application of Biomass from Palm Oil Mill for Organic Rankine Cycle to Generate Power in North Sumatera Indonesia," in *IOP Conference Series Materials Science and Engineering*, 2017, pp. 1–7. doi: DOI:10.1088/1757-899X/180/1/012035.

[26] R. K. and H. H. Rozzeta Dolah, "A Comprehensive Review on Biofuels from Oil Palm Empty Bunch (EFB): Current Status, Potential, Barriers and Way Forward," *Susatinability*, vol. 13, pp. 1–29, 2021, doi: 10210. https://doi.org/10.3390/su131810210.

[27] S. H. Chang, "An Overview of empty fruit bunch from oil palm as feedstock for bio-oil productionn," *Biomass Bio Energy*, vol. 62, pp. 174–181, 2014.

[28] M. Triantafyllidis, K.S.; Lappas, A.A.; Stocker, *The Role of Catalysis for The Sustainable Production of Bio-Fuels and Bio-Chemicals.* 2013. [Online]. Available: https://www.academia.edu/36287906/The_Role_of_Catalysis_for_the_Sustainable_Production_of_Bio_fuels_and_Bio_chemicals

[29] S. . Dolah, R.; Hamdan, H.; Muhid, N.; Yahaya, H.; Rashidi, K.A.; Rashidi, "Second Generation Catalytic Pyrolysis of Oil Palm Empty Fruit Bunches into Bio Oil," 2016.

[30] Y.Yang,J.G.Brammer,D.G.Wright,J.A.ScottaC.Serrano, "Combined heat and power from the intermediate pyrolysis of biomass materials: performance, economics and environmental impact," *Appl. Energy*, vol. 191, pp. 639–652, 2017, doi: https://doi.org/10.1016/j.apenergy.2017.02.004.

[31] R. Kumar, R.S.; Sivakumar, S.; Joshuva, A.; Deenadayalan, G.; Vishnuvardhan, "Bio-fuel Production from Martynia annua L. Seeds using Slow Pyrolysis Reactor and its Effects on Diesel Engine Performance, Combustion and Emission Characteristics," *Energy*, vol. 217, 2021, doi: https://doi.org/10.1016/j.energy.2020.119327.

[32] S. . Sembiring, K.C.; Rinaldi, N.; Simanungkalit, "Bio-oil from Fast Pyrolysis of Empty Fruit Bunch at Various Temperature," *Energy Procedia*, vol. 65, pp. 162–169, 2015.

[33] Mohsin Raza; Abrar Inayat; Ashfaq Ahmed; Farrukh Jamil;Chaouki Ghenai; Salman R. Naqvi; Abdallah Shanableh;Muhammad Ayoub; Ammara Waris; and Young-Kwon, "Progress of the Pyrolyzer Reactors and Advanced Technologies for Biomass Pyrolysis Processing," *Susatinability*, vol. 13, no. 9, pp. 1–42, 2021, doi: https://doi.org/10.3390/su131911061.

[34] W. W. M. H. A. Y. H. Wan Nor Roslam, "A review on bio-oil production from biomass by using pyrolysis method," *Renew. Sustain. Energy Rev.*, vol. 16, no. 8, 2012, doi: https://doi.org/10.1016/j.rser.2012.05.039.

[35] A. Hornung, *Transformation of Biomass: Theory to Practice*. Wiley-VCH Verlag GmbH & Co. KGaA, 2014. [Online]. Available: https://www.wiley.com/en-gb/Transformation+of+Biomass%3A+Theory+to+Practice-p-9781118693643

[36] Y. Zhang, L.; Liu, R.; Yin, R.; Mei, "Upgrading of bio-oil from biomass fast pyrolysis in China: A review," *Renew. Sustain. Energy Rev*, vol. 14, pp. 66–72, 2013.

[37] S. Kim, S.W.; Koo, B.S.; Ryu, J.W.; Lee, J.S.; Kim, C.J.; Lee, D.H.; Kim, G.R.; Choi, "Bio-oil from the pyrolysis of palm and Jatropha wastes in a fluidized bed," *Fuel Process. Technol.*, vol. 108, pp. 118–124, 2013, doi: https://doi.org/10.1016/j.fuproc.2012.05.002.

[38] S. . Yahaya, H.; Hamdan, H.; Dolah, R.; Muhid, N.; Rashidi, K.A.; Rashidi, "Catalytic fast-pyrolysis process design and equipment setup for converting palm oil empty fruit bunch biomass to bio-oil," *Adv. Res. Fluid Mech. Therm. Sci*, vol. 32, pp. 1–8, 2017.

[39] S. W. A. V. B. Banks;, *Catalytic fast pyrolysis for improved liquid quality*, 2nd ed. 2016.

[40] H. . Pogaku, R.; Hardinge, B.S.; Vuthaluru, H.; Amir, "Production of bio-oil from oil palm empty fruit bunch by catalytic fast pyrolysis: A review," *Biofuels*, vol. 7, pp. 647–660, 2016.

[41] M. Z. . Mohamed, A.R.; Hamzah, Z.; Daud, "Optimization of the pyrolysis process of empty fruit bunch (EFB) in a fixed-bed reactor through a central composite design," in *AIP Conf.*, 2016, pp. 1172–1177. doi: https://doi.org/10.1063/1.488775.

[42] M. Perkins, G.; Bhaskar, T.; Konarova, "Process development status of fast pyrolysis technologies for the manufacture of renewable transport fuels from biomass," *Energy Rev.*, vol. 90, pp. 292–315, 2018.

[43] Z. Mohamed, A.R.; Hamzah, Z.; Daud, M.Z.M.; Zakaria, "The effects of holding time and the sweeping nitrogen gas flowrates on the pyrolysis of EFB using a fixed bed reactor," *Procedia Eng.*, vol. 53, pp. 185–191, 2013.

[44] S. . Yahaya, H.; Hamdan, H.; Dolah, R.; Muhid, N.; Rashidi, K.A.; Rashidi, "Catalytic fast-pyrolysis process design and equipment setup for converting palm oil empty fruit bunch biomass to bio-oil," *Adv. Res. Fluid Mech. Therm. Sci.*, vol. 32, no. 1–8, 2017.

[45] Y. Dai, X., Wu, C., Li, H., and Chen, "The fast pyrolysis of biomass in CFB reactor," *Energy Fuels*, vol. 14, pp. 552–557, 2000, doi: 10.1021/ef9901645.

[46] Y. Chan, Y.; Dang, V.I.; Yusup, S.; Lim, M.T.; Zain, A.M.; Uemura, "Studies on Catalytic Pyrolysisof Empty Fruit Bunch (EFB) using Taguchi's L9 Orthogonal Array," *J. Energy Inst.*, vol. 87, pp. 227–234, 2014.

[47] Shahidul et al., "METHANE PRODUCTION POTENTIAL OF POME: A REVIEW ON WASTE-TO-ENERGY [WTE] MODEL," *Sci Int*, vol. 30, no. 5, pp. 717–728, 2018.

[48] L. Rocchetti, F. Vegliò, B. Kopacek, and F. Beolchini, "Environmental impact assessment of hydrometallurgical processes for metal recovery from WEEE residues using a portable prototype plant," *Environ. Sci. Technol.*, 2013, doi: 10.1021/es302192t.

[49] A. Talero, G.F.; Rincon, S.L.; Gonzalez, "Use of Colombian Oil Palm Wastes for Pellets Production: Reduction of the Process Energy Consumption by Modifying Moisture Conten," in *In Proceedings of the 6th International Conference on Engineering for Waste and Biomass Valorisation*, 2016, pp. 23–26.

[50] L. W. C. and C. Y. Y. Chin Kit Ling, H`ng Paik San, Eng Hooi Kyin, Lee Seng Hua, "Yield and Calorific Value of Bio Oil Pyrolysed from Oil Palm Biomass and its Relation with Solid Residence Time and Process Temperature," *Asian J. Sci. Res.*, vol. 8, no. 352–358, 2015, doi: 10.3923/ajsr.2015.351.358.

[51] A. P. Pranshu Shrivastava , Anil Kumar, Perapong Tekasakul , Su Shiung Lam, "Comparative Investigation of Yield and Quality of Bio-Oil and Biochar from Pyrolysis of Woody and Non-Woody Biomasses," *Energies*, vol. 14, no. 1092, 2021, doi: https://doi.org/10.3390/en14041092.

[52] S. Y. Xu Y, Hu X, Li W, "Preparation and Characterization of Bio-oil from Biomass," in *Progress in Biomass and Bioenergy Production*, 2011. doi: DOI: 10.5772/16466.

[53] A. Ekman Nilsson *et al.*, "A Review of the Carbon Footprint of Cu and Zn Production from Primary and Secondary Sources," *Minerals*, vol. 7, p. 168, Sep. 2017, doi: 10.3390/min7090168.

[54] S. S. Goran Jankes, Marta Trniinic, Mirjana Stamenic, tomislav, "Biomass gasification with CHP production: A review of state of the art technology and near future perspectives," *Therm. Sci.*, vol. 16, no. 1, pp. S115–S130, 2012.

[55] EIA, "Annual energy outlook 2019. U.S. Energy Information Administration," 2019.

[56] Po-ChihKuo and Wei Wu, "Design of Co-gasification from Coal and Biomass Combined heat and Power Generation System," *Energy Procedia*, vol. 75, pp. 1120–1125, 2015.

[57] M. A. Bagherian, K. Mehranzamir, and and S. M. A.

, Shahabaldin Rezania, Zulkurnain Abdul-Malek, Amin Beiranvand Pour, "Analyzing Utilization of Biomass in Combined Heat and Power and Combined Cooling, Heating, and Power Systems," *Process*, vol. 9, no. 6, pp. 1–29, 2021, doi: https://doi.org/10.3390/pr9061002.

[58] M. M. Damirchi, H.; Najafi, G.; Alizadehnia, S.; Mamat, R.; Nor Azwadi, C.S.; Azmi, W.H.; Noor, "Micro Combined Heat and Power to Provide Heat and Electrical Power Using Biomass and Gamma-Type Stirling Engine," *Appl. Therm. Eng.*, vol. 103, pp. 1460–1469, 2016.

[59] E. O. A. M.Börjesson, "Biomass CHP Energy Systems: A Critical Assessment," *Compr. Renew. Energy*, vol. 5, pp. 87–97, 2012, doi: https://doi.org/10.1016/B978-0-08-087872-0.00508-4.

[60] Paul Breeze, "Combined Heat and Power," in *Power Generation Technology*, Second Edi., 2014, pp. 111–127. doi: https://doi.org/10.1016/B978-0-08-098330-1.00006-5.

[61] E. J. J. and M. R. Shahidul M. I., Malcolm M.L., "OPTIMIZATION OF FACTORS AFFECTING BIOGAS PRODUCTION FROM POME," *Sci.Int.(Lahore*, vol. 30, no. 6, pp. 851–859, 2018.

[62] M. I. Shahidul, M.I.1, Malcolm, M.L1. and Eugene, J.J1, Sharafatul, "OPTIMIZING PRODUCTIVITY IN SEPARATING BIOMASS AND ORGANIC MATERIALS FROM PALM OIL MILL EFFLUENT: EXPERIMENT TOWARDS REDUCING CARBON EMISSION FOR CLIMATE CHANGE EFFECT," *Sci.Int.(Lahore*, vol. 32, no. 5, pp. 547–556, 2020.

[63] S. K. Loh, "The potential of the Malaysian oil palm biomass as a renewable energy source," *Energy Convers. Manag.*, vol. 141, pp. 285–298, 2017, doi: https://doi.org/10.1016/j.enconman.2016.08.081.

[64] N. Abdullah and F. Sulaim, "The Oil Palm Wastes in Malaysia," in *Biomass Now - Sustainable Growth and Use*, 2013. doi: 10.5772/55302.

[65] M. I. Shahidul, M. L. Malcolm, J. J. Eugene, and R. Mamunur, "Optimization of factors affecting biogas production from POME," *Sci. Int.*, vol. 30, no. 6, pp. 851–859, 2018.

[66] W. S. Boon Siang Tan, Haslenda Hashim, Zarina Ab Muis, Nor Alafiza Yunus and Ho, "Potential of Energy Recovery from an Integrated Palm Oil Mill with Biogas Power Plant," *Chem. Eng. Trans.*, vol. 63, pp. 253–258, 2018, doi: DOI: 10.3303/CET1863043.

[67] A. Junqueira, T.L., Chagas, M.F., Gouveia, V.L.R., Rezende, M.C.A.F., Watanabe, M.D.B., Jesus, C.D.F., Cavalett, O., Milanez, A.Y., Bonomi, "Techno-economic analysis and climate change impacts of sugarcane biorefineries considering different time horizons," *Biotechnol. Biofuels*, vol. 10, no. 12, 2017, doi: https://doi.org/10.1186/.

[68] L. C. I. Prasetyaning, "Promotion of Least Cost Renewables in Indonesia," 2014. [Online]. Available: https://tuewas-asia.org/wp-content/uploads/2017/06/overview_biomass_study_LCORE_FIN_withcover_smallsize.pdf

[69] B. Pantaleo, A.M.; Camporeale, S.; Fortunato, "Small scale biomass CHP: Techno-economic performance of steam vs gas turbines with bottoming ORC," *Energy Procedia*, vol. 82, pp. 825–832, 2015.

[70] ANNIES Export NZ ltd, "Identification of Potential Pilot Projects for Waste to Energy in Indonesia's Agroindustry.," Jakarta Indonesia, 2012. [Online]. Available: https://tuewas-asia.org/wp-content/uploads/2017/06/overview_biomass_study_LCORE_FIN_withcover_smallsize.pdf

[71] S. S. Harsono, A. Prochnow, P. Grundmann, A. Hansen, and C. Hallmann, "Energy balances and greenhouse gas emissions of palm oil biodiesel in Indonesia," *GCB Bioenergy*, vol. 4, no. 2, pp. 213–228, Mar. 2012, doi: 10.1111/j.1757-1707.2011.01118.x.

[72] S. K. Loh *et al.*, "Biogas Capture-A Means of Reducing Greenhouse Gas Emissions from Palm Oil Mill Effluent," 2017.

[73] Eugene JJ, Shahidul MI, and Mamunur R, "Optimizing Organic Materials Reduction from Hazardous Industrial Bio-Effluent by the aid of C/N Enriched Inoculum: An Approach to use Traditional Anaerobic Reactor to Achieve Environmental Sustainability," *Sci.Int.(Lahore)*, vol. 31, no. 4, pp. 649–654, 2019.

[74] A. H. Shamsuddin, "Development of renewable energy in Malaysia: Strategic initiatives for carbon reduction in the power generation sector," *Procedia Eng.*, vol. 49, pp. 384–391, 2012, doi: https://doi.org/10.1016/j.proeng.2012.10.150.

[75] C. Saswattecha, K., Cuevas Romero, M., Hein, L., Jawjit, W., & Kroeze, "Non-CO2 greenhouse gas emissions from palm oil production in Thailand," *J. Integr. Environ. Sci.*, vol. 12, pp. 67–85, 2015, doi: https://doi.org/10.1080/1943815X.2015.1110184.