CHEMICAL ENGINEERING TRANSACTIONS

VOL. 97, 2022

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Jeng Shiun Lim, Nor Alafiza Yunus, Jiří Jaromír Klemeš

ISBN 978-88-95608-96-9; **ISSN** 2283-9216

DOI: 10.3303/CET2297048

Bioenergy Generation Potential of Empty Fruit Bunch and Waste Tire Through Microwave Pyrolysis: An Energy Balance Analysis

Guo Ren Mong[a,*], Chin Seng Liew[b], William Woei Fong Chong[c], Rubia Idris[d], Jo-Han Ng[e], Meng Choung Chiong[f]

[a]School of Energy and Chemical Engineering, Xiamen University Malaysia, Jalan Sunsuria, Bandar Sunsuria, 43900, Sepang, Selangor, Malaysia
[b]Department of Fundamental and Applied Sciences, HICoE-Centre for Biofuel and Biochemical Research, Institute of Self-Sustainable Building, Universiti Teknologi PETRONAS, 32610, Seri Iskandar, Perak Darul Ridzuan, Malaysia
[c]School of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310, Skudai, Johor, Malaysia
[d]Faculty of Science and Natural Resources, Universiti Malaysia Sabah, Jalan UMS, 88400, Kota Kinabalu, Sabah, Malaysia
[e]Faculty of Engineering and Physical Sciences, University of Southampton Malaysia (UoSM), 79200, Iskandar Puteri, Johor, Malaysia
[f]Department of Mechanical Engineering, Faculty of Engineering, Technology & Built Environment, UCSI University, 56000, Kuala Lumpur, Malaysia
guoren.mong@xmu.edu.my

Energy has been needed more than ever, especially in the 21st century, for daily activities. The generation of energy from fossil sources fuels the industry's evolution but induces irreversible damage to the environment. Focus has been shifting towards bioenergy for a greener and sustainable approach in energy production, especially on biomass waste due to its abundant source that is not limited to geographical and climate changes. Empty fruit bunch (EFB) and waste tire (WT) have been an alarming waste due to industrialization. Unsystematic management of this waste has caused irreversible environmental damage and loss of valuable resources. Pyrolysis has been discovered as an effective process to effectively and safely manage, dispose and valorize waste into higher-value products. Pyrolysis is an energy-intensive process that is speculative to be not sustainable in the long run. This work will study the bioenergy generation potential of EFB and WT through microwave pyrolysis. The result shows that the bioenergy retrieved from WT and EFB is at 93.7 % and 90.99 %, portraying a minor amount of energy lost. Considering the energy consumption during the microwave pyrolysis process, a net energy profit (20.66 %) can be gained from WT, EFB records a loss of 81.17 %. This is attributed to the content of feedstock where EFB contains higher moisture and oxygenated composition, leading to the generation of products with lower heating value. The outcome does not reduce the efficiency of EFB valorization through microwave pyrolysis as the bio-oil contains valuable chemicals like phenols that can be retrieved as a biochemical source. Overall, the bioenergy generation is better when WT is used as feedstock. Bioenergy analysis should be conducted on the co-pyrolysis process to evaluate the feasibility of co-managing the waste, besides improving feedstock flexibility for this technology.

1. Introduction

Waste management has always been a problem to tackle. The alarming waste generation rate further increases the difficulty of solving this issue, especially in developing countries. In Malaysia, an estimate of 22-23 Mt of empty fruit bunch (EFB) is being generated annually, with only 10 % of this waste being reused, and others are being disposed of (Anuar et al., 2019). The global rubber consumption has a major attribution towards the tire manufacturing industries and generating about 18 Mt of waste tire annually (Wang et al., 2020). When being disposed of through unsystematic means, these wastes will cause irreversible environmental damage and lead to the degrading of human health. Conventionally, EFB will be left to decompose naturally within palm

Paper Received: 25 May 2022; Revised: 18 July 2022; Accepted: 29 July 2022
Please cite this article as: Mong G.R., Liew C.S., Chong W.W.F., Idris R., Ng J.-H., Chiong M.C., 2022, Bioenergy Generation Potential of Empty Fruit Bunch and Waste Tire Through Microwave Pyrolysis: An Energy Balance Analysis, Chemical Engineering Transactions, 97, 283-288 DOI:10.3303/CET2297048

plantations; some will be collected and burned. WT is usually sent to a landfill if not illegally burned. There is a need to identify new, sustainable and green pathway to properly managed the wastes. Pyrolysis has been discovered as a good way to valorize waste into higher value products (Mong et al., 2021b). Experiments on EFB pyrolysis have reported that the biochar produced can be a good candidate for soil amendment and carbon sequestration. WT pyrolysis is reported to derive diesel-liked liquid fuel (Idris et al., 2021) and activated carbon (Malise et al., 2020) for power production and water treatment purposes. It is undeniable that pyrolysis seems to be the solution to these enormous amounts of waste. The process has a drawback that restricts the wide adoption of such technology.
Pyrolysis is a thermal decomposition process that requires a high amount of energy (Liew et al., 2021). Research has been conducted to evaluate the energy-intensiveness and sustainability of pyrolysis (Chico-Proano et al., 2021). The pyrolysis of waste has received reports on energy deficit originating from the formation of non-valuable products (Mong et al., 2020) and inefficiency losses within the conversion system like endothermic and exothermic reactions (Jesus et al., 2018). The bioenergy content of each product derived through pyrolysis contributes to the overall energy profit of the process. It is important to have a thorough energy analysis conducted to evaluate the effectiveness of pyrolysis process in harvesting bioenergy from waste. Despite that there are plenty of research conducted on the pyrolysis of EFB and WT, a complete energy analysis has rarely been reported. Sulaiman and Abdullah (2011) only analyse the bio-oil production from fast pyrolysis of EFB and there is no report on the yield and characteristics of solid and gas products. The bio-oil yield of 36 wt% from EFB fast pyrolysis at 450 °C is retrieved in two states – 60 % organic phase and 40 % aqueous phase. The organic phase contains low moisture content (7.9 %) and high carbon content (69.35 %) with a high viscosity that hardly flows at room temperature. Fang et al. (2018) conducted a detail analysis on the solid, liquid and gas yield from the microwave pyrolysis of WT, but there is no record of energy balance analysis. The microwave pyrolysis of WT at 1,000 W and 40 min produce biochar of 24.83 MJ/kg and 80.25 wt% of carbon, indicating the potential for fuel application. The bio-oil contains high benzene and hydrocarbon compounds but with low oxygenated compounds, showing potential as transportation fuel additives. There is still much research gap to be filled from the bioenergy profitability aspect. This study will analyze the microwave pyrolysis process's energy distribution and profit when EFB and WT are valorized, leading to a thorough insight about the energy profitability of waste valorization through microwave pyrolysis technology. Besides, an additional section discussing the carbon footprint of the process will also be conducted to evaluate the carbon footprint of such a process.

2. Methods

2.1 Experiment and characterization

A lab-scale, batch-reactor, microwave pyrolysis rig has been setup to valorize EFB and WT and end products in biochar, bio-oil and gas were retrieved. A 1 kW rated domestic microwave oven with a rated efficiency of 69.5 % was used as the heating source. The temperature within the reactor is kept constant with a temperature controller and a K-type thermocouple. A quartz reactor with a 3-neck lid was used to hold the feedstock of EFB or WT. A constant flow of pure N_2 gas was utilized to ensure an inert environment and the hot volatile evolved during pyrolysis is transferred to a set of condensers maintained at 5 °C, aided by a water bath circulator. The experiment was conducted at 500 °C for 1 h. At the end of experiment, the solid leftover within the reactor is collected as biochar, the liquid condensate is collected as bio-oil and the uncondensed vapor is collected as biogas. The detail experimental design and procedure are recorded elsewhere (Idris et al., 2021). The products obtained were sent for thorough characterization to identify their composition and calorific value. The higher heating value (HHV) of biochar is measured using a bomb calorimeter. The HHV of bio-oil is calculated using DIN 51900 standard formula as displayed in Eq(1).

$$HHV = \frac{34\ C + 124.3\ H + 6.3\ N + 19.3\ S - 9.8\ O}{100} \tag{1}$$

The C, H, S, A, O and N denote the mass fractions (wt%) of carbon, hydrogen, sulphur, ash, oxygen, and nitrogen contents. The LHV of the gaseous product is calculated using Eq(2).

$$LHV = \frac{(H_2*107.98) + (CO*126.36) + (CH_4*358.18) + (C_2H_2*56)}{1000} \tag{2}$$

The input and output of the microwave pyrolysis process is shown in Table 1.

2.2 Energy analysis and balance

The bioenergy content of all three types of products obtained from the microwave pyrolysis process is calculated using Eq(3).

$$Bioenergy\ Yield\ (MJ) = F_M * Y_P * CV_P \tag{3}$$

Where F_M is the mass of feedstock used during experiment, Y_P is the yield of product from the microwave pyrolysis process and CV is the calorific value and the subscript of P and F represents the product and feedstock. The bioenergy distribution is evaluated from the feedstock initial HHV, according to Eq(4).

$$Bioenergy\ Distribution\ (\%) = \frac{Bioenergy\ Yield}{F_M * CV_F} * 100 \tag{4}$$

The energy balance analysis is conducted considering the energy input during the microwave pyrolysis process and the energy output, as retrieved from the products in Eq(3). The outcome of attaining an energy profit or energy deficit is measured using Eq(5)

$$Energy\ Profit/Deficit\ (\%) = \frac{\sum Bioenergy\ Yield}{Energy\ Consumed} * 100 \tag{5}$$

Table 1: The inputs and outputs of the microwave pyrolysis process of EFB and WT

Input	Description		Unit	
Microwave Power	0.7		kWh	
Processing Time	1		h	
Temperature	500		°C	
Feedstock	0.1		kg	
EFB	17.9		MJ/kg	
WT	39.9		MJ/kg	
Catalyst	Activated Carbon			
Output	EFB		WT	
	Yield (%)	Heating Value (MJ/kg)	Yield (%)	Heating Value (MJ/kg)
Biochar	35.11	25	39.79	42.5
Bio-oil	38.26	11.76	39.12	43.05
Gas	26.63	14.63	22.09	18.52

2.3 Carbon footprint analysis

The carbon sequestration credits (CSC) for the products derived were measured through Eq(6). In this work, the product with carbon sequestration potential is biochar as it contains stable carbons and can withstand degradation when buried underground. The bio-oil and gas products are assumed to be utilize as biofuel with no carbon sequestration potential.

$$CSC = Y_P * CC_P * R_{C/CO_2} * CS_P \tag{6}$$

The CC_P refers to the carbon content of product, R_{C/CO_2}refers to the carbon to CO_2 equivalent ratio (using a value of 12/44) and CS_P is the carbon stability of product, where CS for biochar is reported at 0.7 (Luo et al., 2021).

The carbon footprint of the process is analyzed by evaluating the CO_2-eq emission of the process (mainly from electrical consumption) and the carbon storage potential of the products, according to Eq(7). The carbon emission from the consumption of energy supplied by the power grid is taken as 373.48 g CO_2-eq/kWh, considering key global warming potential gases like CO, CO_2, CH_4 and NO_x (Spath and Mann, 2000). The microwave pyrolysis process is calculated to consume a power of 0.7 kWh and the emission is at 261.4 g CO_2-eq. The products used for energy production are assumed to release biogenic CO_2 during combustion and will not be accounted for its carbon footprint.

$$Carbon\ footprint = (E_A + CSC) - \sum CO_2 - eq_{Process} \tag{7}$$

E_A refers to the avoided emission from energy production through fossil fuels like coal (replaced by biochar), fuel oil (replaced by bio-oil) and natural gas (replaced by gas product). The avoided emission is calculated by evaluating the net emission of CO_2-eq with reference of unit energy produced (kWh). According to the EPA (2014), coal coke, residue fuel oil No.6 and natural gas will have an emission of 113.67 kg CO_2/mmBTu, 75.1 kg CO_2/mmBTu and 53.06 kg CO_2/mmBTu. The products derived with acceptable fuel properties will be assumed to be used for bioenergy production. The amount of bioenergy produced will be assumed to directly substitute fossil fuels, calculating the avoided emissions.

3. Results and discussion

3.1 Product yield and energy content

Table 2 display the bioenergy yield within each product derived from the microwave pyrolysis of EFB and WT. It can be observed that the solid product (biochar) contains the highest yield with 52.75 % and 42.38 % of bioenergy being transferred from the original feedstock. The HHV of WT-biochar (42.5 MJ/kg) is higher than EFB-biochar (25 MJ/kg), the bioenergy transferred is higher for EFB-biochar. This can be attributed to the initial calorific value of the waste where WT (39.9 MJ/kg) is much higher than EFB (17.9 MJ/kg). The bio-oil within WT has a higher bioenergy yield with up to 41.13 % being distributed within the liquid product, while liquid derived from EFB only contains 25.05 %. This showcase the superiority of WT for bio-oil yield with high energy content. The lower bioenergy distributed within the liquid yield for EFB is due to the presence of oxygenated compounds and moisture content, lowering the energy content. Biomass-derived bio-oil generally contain high oxygenated compounds giving it a lower calorific value (Miskolczi et al., 2020). Nonetheless, the bio-oil from biomass like EFB contains valuable chemicals (mainly from oxygenated compounds) like pyridine, phenols and ketones that can be extracted as bio-chemical source. Gas products from EFB and WT contain the least bioenergy distributed with 21.68 % and 10.25 %. This is due to the non-condensable vapor generated during microwave pyrolysis containing small gaseous molecules like CO, CO_2, H_2 and a small portion of CH_4 with lower heat capacity than larger gaseous compounds C_2H_6 and C_3H_8. Gaseous product yield is lower than solid and liquid products, having a lower amount of bioenergy. Microwave pyrolysis aided by activated carbon has been reported to produce a higher yield of CO and H_2.
Summarizing the total bioenergy content within the solid, liquid and gas products, it has been found that the microwave pyrolysis process can retrieved up to 93 % of energy contained within the raw feedstock and only a minor amount of energy is lost. The bioenergy lost during microwave pyrolysis may be attributed to the formation of products like water and coke (Mong et al., 2020). Microwave pyrolysis can retrieve a higher energy content for WT, mainly due to the nature of feedstock (fossil-derived product with low moisture content of 0.92 %). EFB contains 3.96 % of moisture after being pre-treated before pyrolysis. Water may also be formed from the reaction between oxygenated compounds during the experiment. It is to note that the oxygen composition within EFB (50.44 %) is higher than WT (10.81 %). The energy profit of the microwave pyrolysis when WT is used as feedstock is better than EFB. WT achieves an overall 20.66 % energy profit after considering the energy consumed during the valorization process (estimated to be 0.7 kWh). On the other hand, EFB attains an energy deficit of 81.17 %. The large discrepancy is due to the initial energy content of raw feedstock. WT has a higher energy content (39.9 MJ/kg) due to its fossil-based properties, biomass sources like EFB have a lower energy content (17.97 MJ/kg). As both feedstocks are processed using the same experimental setup and consume the same amount of energy, the feedstock with an initial lower energy content will have a lower energy yield. In addition, the bio-liquid with high oxygenated compounds and low heating value due to the generation of water during the microwave pyrolysis of EFB contributes to the process's energy deficit. The outcome of this study brings to view the possibility of co-pyrolysing different types of waste simultaneously to improve the overall energy profit.

Table 2: Energy yield, distribution and profit for EFB and WT for microwave pyrolysis

Feedstock/	EFB			WT		
Products	Biochar	Bio-oil	Gas	Biochar	Bio-oil	Gas
Bioenergy Yield (MJ)	0.95	0.45	0.39	1.69	1.64	0.41
Bioenergy Distribution (%)	52.75	16.56	21.68	42.38	40.94	10.25
Energy Profit/Deficit (%)		-81.17			20.66	

3.2 Carbon footprint analysis

The carbon footprint was evaluated based on emission generated from the microwave pyrolysis process, carbon sequestration potential of the product and avoided emission from fossil sources. Figure 1 display the net carbon emission of the process where the microwave pyrolysis of EFB records a positive carbon emission of 0.09 kg CO_2 and WT records a negative carbon footprint of -0.14 kg CO_2. EFB has a net positive carbon emission due to several factors. Firstly, the bioproducts derived from EFB is lower in energy content, capable of replacing a lower amount of fossil fuel. Secondly, the carbon content of biochar-EFB is lower, reducing the CSS potential. The scenario is different for WT as it has a higher energy content and carbon content, which can balance out the emitted CO_2 during microwave pyrolysis. Overall, the work portrays the possibility of microwave pyrolysis to be a negative carbon emission technology in waste valorization and management. WT has a better environmental footprint as the derived products contains higher energy 0content that can replace more fossil sources to generate the same amount of energy.

Despite the less attractive findings on the EFB feedstock with energy deficit and positive carbon emission, microwave pyrolysis technology has been proven to be an effective waste-to-energy technology that is both sustainable and environmentally friendly. The drawbacks can be overcome by integrating both feedstock of EFB and WT as blends, to be co-pyrolyzed under the same operating condition. Synergism has been reported to exist between the co-pyrolysis of EFB and WT (Mong et al., 2021a), which might positively affect the energy yield. These analyses can be proposed in the future study.

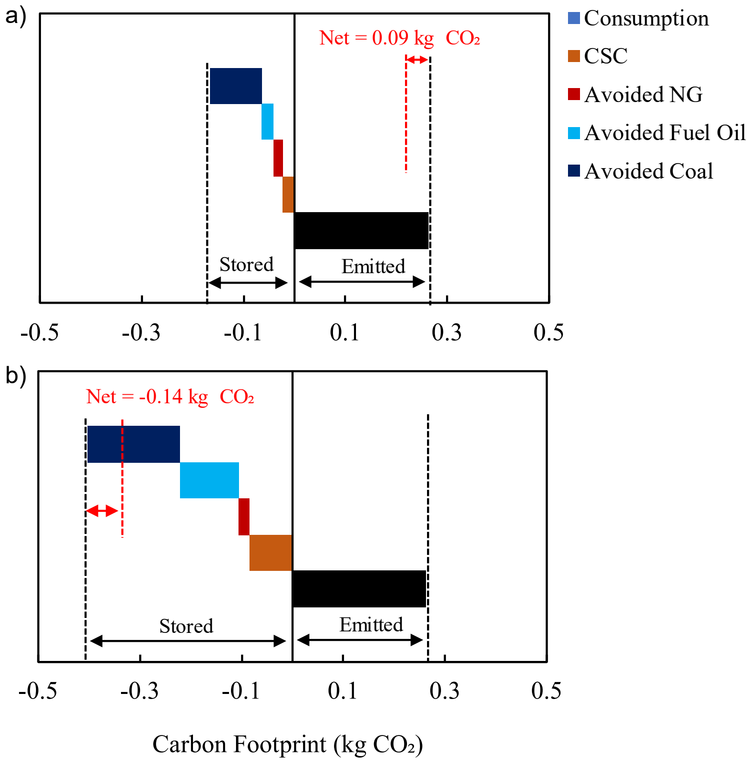

Figure 1: The net carbon emission from the microwave pyrolysis of (a) EFB and (b) WT

4. Conclusions

This study demonstrates a bioenergy and carbon footprint analysis between EFB and WT, which has undergone valorization through microwave pyrolysis. WT is able to attain a higher bioenergy content of 93.59% and EFB has a lower value of 90.99%. By accounting the energy consumption, WT valorization through microwave pyrolysis achieved an overall energy profit of 20.66 %, mainly due to the raw feedstock having a high calorific value. EFB records an overall energy deficit (-81.17 %) through microwave pyrolysis, mainly due to its higher oxygen composition causing the products generated to be high in oxygenated compounds, lowering the calorific value. Evaluation on the carbon emission of the process demonstrate WT as feedstock successfully achieved a net negative carbon emission of -0.14 kg CO_2. The results demonstrated the possibility of managing and valorizing wastes such as EFB and WT through microwave pyrolysis. The positive results from WT for example the negative carbon emission and positive bioenergy production can serve as a trade-off to overcome the less desirable results when EFB is processed. This calls for the possibility in co-managing different types of waste, in this context it will be WT and EFB. The present of synergism when different wastes is being process will be of interest where the target is to further increase the bioenergy generation and lower the environmental footprint of such process.

Acknowledgments

This research was supported by Xiamen University Malaysia Research Fund (Grant No: XMUMRF/2022-C9/IENG/0045)

References

Anuar N.I.S., Zakaria S., Gan S., Chia C.H., Wang C., Harun J., 2019, Comparison of the morphological and mechanical properties of oil palm efb fibres and kenaf fibres in nonwoven reinforced composites, Industrial Crops and Products (127), 55-65.

Chico-Proano A., Manos G., Papageorgiou G.L., Fragaa E.S., 2021, Heating strategies in cellulose pyrolysis as an alternative for targeting energy efficient product distribution, Chemical Engineering Transactions (86), 61-67.

EPA, 2014, Emission factors for greenhouse gas inventories, Environment Protection Agency < https://www.epa.gov/sites/default/files/2015-07/documents/emission-factors_2014.pdf> accessed 20.5.2022.

Fang S., Gu W., Dai M., Xu J., Yu Z., Lin Y., Chen J., Ma X., 2018, A study on microwave-assisted fast co-pyrolysis of chlorella and tire in the N_2 and CO_2 atmospheres, Bioresource Technology (250), 821-827.

Idris R., Chong W.W.F., Ali A., Idris S., Tan W.H., Md Salim R., Mong G.R., Chong C.T., 2021, Pyrolytic oil with aromatic-rich hydrocarbons via microwave-induced in-situ catalytic co-pyrolysis of empty fruit bunches with a waste truck tire, Energy Conversion and Management (244), 114502.

Jesus M.S., Napoli A., Trugilho P.F., Abreu Júnior Á.A., Martinez C.L.M., Freitas T.P., 2018, Energy and mass balance in the pyrolysis process of eucalyptus wood, Cerne (24), 288-294.

Liew C.S., Kiatkittipong W., Lim J.W., Lam M.K., Ho Y.C., Ho C.D., Ntwampe S.K.O., Mohamad M., Usman A., 2021, Stabilization of heavy metals loaded sewage sludge: Reviewing conventional to state-of-the-art thermal treatments in achieving energy sustainability, Chemosphere (277), 130310.

Luo H., Cheng F., Yu B., Hu L., Zhang J., Qu X., Yang H., Luo Z., 2021, Full-scale municipal sludge pyrolysis in china: Design fundamentals, environmental and economic assessments, and future perspectives, Science of the Total Environment (795), 148832.

Malise L., Rutto H., Seodigeng T., Sibali L., Ndibewu P., 2020, Adsorption of lead ions onto chemical activated carbon derived from waste tire pyrolysis char: Equilibrium and kinetics studies, Chemical Engineering Transactions (82), 421-427.

Miskolczi N., Zsinka V., Tóth O., Eller Z., Gao N., Cui Q., Bobek J., 2020, Co-pyrolysis-reforming of biomass and residues from waste polymer pyrolysis for CO_2 reduction and syngas enhancement, Chemical Engineering Transactions (81), 1195-1200.

Mong G.R., Chong C.T., Ng J.-H., Chong W.W.F., Lam S.S., Ong H.C., Ani F.N., 2020, Microwave pyrolysis for valorisation of horse manure biowaste, Energy Conversion and Management (220), 113074.

Mong G.R., Chong W.W.F., Ng J.H., Chong C.T., Idris R., Abas M.A., Chiong M.C., 2021a, Co-pyrolysis of empty fruit bunch and waste tire a kinetics and synergism analysis, Chemical Engineering Transactions (89), 13-18.

Mong G.R., Chong W.W.F., Nor S.A.M., Ng J.-H., Chong C.T., Idris R., Too J., Chiong M.C., Abas M.A., 2021b, Pyrolysis of waste activated sludge from food manufacturing industry: Thermal degradation, kinetics and thermodynamics analysis, Energy (235), 121264.

Spath P.L., Mann M.K., 2000, Life cycle assessment of a natural gas combined-cycle power generation system, National Renewable Energy Laboratory

Sulaiman F., Abdullah N., 2011, Optimum conditions for maximising pyrolysis liquids of oil palm empty fruit bunches, Energy (36), 2352-2359.

Wang C., Zhao B., Tian X., Wang K., Tian Z., Han W., Bian H., 2020, Study on the pyrolysis kinetics and mechanisms of the tread compounds of silica-filled discarded car tires, Polymers (Basel) (12), 810.