talenta PUBLISHER

Eco Chemical Engineering Journal

Journal homepage: https://talenta.usu.ac.id/EcoChe

Design and Engineering Assessment of a Microwave-Assisted Pyrolysis Reactor for Biochar Production from Oil Palm Empty Fruit Bunch Pellets

Durain Parmanoan[*1], Dori Yuvenda[1] , Yolli Fernanda[1], Sri Rizki Putri Primandari[1], Kuntum Khoiro Ummatin[2], Izzati Winda Murti[2], Dwi Annisa Fithry[3]

[1]*Department of Mechanical Engineering, Faculty of Engineering, Universitas Negeri Padang, Padang 25171, Indonesia*

[2]*Universitas Internasional Semen Indonesia, Kompleks PT. Semen Indonesia (Persero) Tbk., Jl. Veteran, Gresik, Jawa Timur, 61122, Indonesia*

[3]*Universitas Muhammadiyah Riau, Jl. Tuanku Tambusai, Pekanbaru, Riau 28294, Indonesia*

*Corresponding Author: durain_siregar@unp.ac.id

Article info

Article history:
Received 18 September 2026
Revised 19 October 2026
Accepted 21 October 2026
Available online xxx

E-ISSN:
P-ISSN:

How to cite:
D. Parmanoan, D. Yuvenda, Y. Fernanda, S. R. P. Primandari, K. K. Ummatin, I. W. Murti, D. A. Fithry, "Design and Engineering Assessment of a Microwave-Assisted Pyrolysis Reactor for Biochar Production from Oil Palm Empty Fruit Bunch Pellets," Eco Chemical Engineering Journal, Vol. 1 No. 1.

This work is licensed under a Creative Commons Attribution-ShareAlike 4.0 International.

http://doi.org/10.26594/register.v6i1.idarticle

Abstract

The microwave assisted pyrolysis provided a fast volumetric heating for converting lignocellulosic biomass to biochar. However, the implementation at laboratory scale needs coordinated controlling among heating system, handling of inert gas, temperature controller, steam condensation, and gas collection. This research designed and assembled microwave assisted pyrolysis at laboratory scale for making pellets from empty fruit bunch (EFB) and evaluated its engineering configuration and operation condition range. EFB pellets with diameter of 6–8 mm and long of 10–12 mm was processed for 15 min. Microwave used power level of 450, 500, 550, dan 600 W, mass of biomass of 100, 150, 200, and 250 g. This system integrated with a 30 L microwave chamber with maximum power of 1,200 W, inlet and outlet nitrogen duct, thermocouple, glassware for vapor condensation, a 47 L cooling water reservoir, peristaltic pump, gas trap and gas container. Based on regulated power and time process, the input of nominal microwave energy in the range of 0.1125–0.1500 kWh per batch with equivalent to 0.45–1.50 kWh kg^{-1} in the range of used feed mass. This assembled configuration provided a compact experimental platform to systematically evaluate the effect of microwave power and biomass amount, thus to physically separate heating, condensation, and permanent gas handling stages. Quantitative optimization of biochar yield and biochar quality still require characterized data of product for the best result of this research.

Keywords: Biochar, Pellets, Microwave-assisted pyrolysis, Empty fruit bunch, Reactor design

1. Introduction

Processing of palm oil fruits produce a large amount of lignocellulosic residue, included palm oil empty fruit bunches (EFB). Conversion of this biomass to biochar offers the thermochemical process to produce carbon rich solid which can be utilized as fuel precursor, adsorbent precursor, soil amendment, or carbon material, depend on the properties of final product [1], [6], [10]. Pyrolysis is commonly used for this conversion, because it can decompose biomass thermally in the limitation condition of oxygen and produce solid biochar with condensable vapor and also permanent gas [2], [4].

Assisted pyrolysis by microwave differs from conventional external heating because electromagnetic energy can be absorbed directly by material, then enable fast heating volumetrically. Dielectric response of formed biomass and char changed with the increasing of temperature, which affected microwave absorption during the conversion process [3]. Previous research on biomass and oil palm based material showed that

microwave power, particle size, heating rate, and residence time affected distribution and quality of product [2]-[5]. These characters made microwave heating attractive to be applied for compact laboratory system, and also make reactor configuration and process monitoring as important aspects.

Unit pyrolysis of microwave which running well needs more than a heating chamber. The system should provide oxygen limited atmosphere, measure process temperature, flow volatile products from heating zone, condensate liquid fraction, handle non condensable gas, and maintain appropriate cooling capacity. Literature about microwave pyrolysis also showed that hot spots and electrical arcing can occur in the feed condition and certain operation. This part confirm that the need for controlled power and the appropriate reactor construction is very important [7].

The purpose of this research was to design and to assembly a laboratory scale microwave aided pyrolysis reactor system to produce biochar from EFB pellets. This research focused on integration among: heating unit, nitrogen purging unit, temperature measurement, condensation and cooling system, gas trap, and gas collection unit. Power range and loading mass of biomass were also reported from engineering perspective using nominal microwave energy input and specific energy input as design indicators.

2. Method

2.1. Feedstock and design basis

The feed was empty fruit bunch in pellet form. The supplied pellets were reported to have a diameter of 6–8 mm and a length of 10–12 mm approximately, corresponding to a nominal pellet length of about 1 cm. Pelletization was used to improve handling uniformity and increase the bulk energy density of the biomass. The experimental design specified a treatment time of 15 min, microwave power settings of 450, 500, 550, and 600 W, and biomass charges of 100, 150, 200, and 250 g.

Table 1. Design basis and operating variables for the microwave-assisted pyrolysis system.

Parameter	Reported value or level
Feedstock	Oil palm empty fruit bunch (EFB) pellets
Pellet dimensions	6–8 mm diameter; 10–12 mm length
Treatment time	15 min
Microwave power	450, 500, 550, 600 W
Biomass charge	100, 150, 200, 250 g
Atmosphere control	Nitrogen purge/low-oxygen operation
Planned biochar analyses	Yield, moisture, volatile matter, bulk density, calorific value, SEM, FTIR

2.2. Reactor system design and assembly

The reactor train was assembled from a modified microwave oven, nitrogen supply, temperature sensor, vapor-transfer tubing, condensation glassware, cooling-water circulation system, gas trap, and gas bag. The microwave casing was modified to provide process connections for nitrogen introduction and exhaust-vapor removal. A thermocouple was installed for process-temperature monitoring. Volatile products leaving the heated zone were directed to the condensation section before the remaining gas was transferred to the gas trap and gas bag. Figure 1 shows process-flow reconstruction of the microwave-assisted pyrolysis system based on the supplied reactor design.

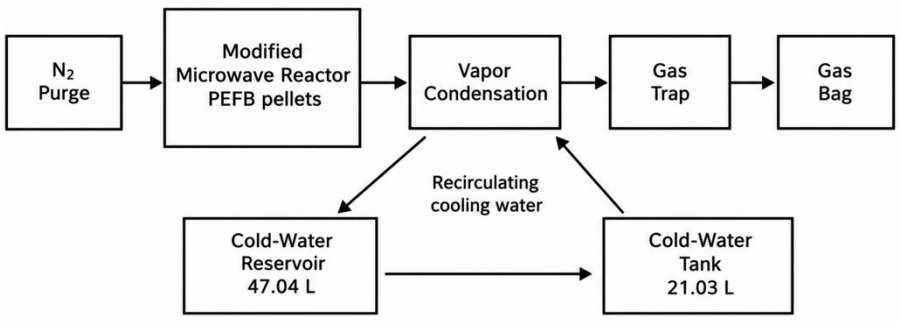


Figure 1. Process-flow of the microwave-assisted pyrolysis system.

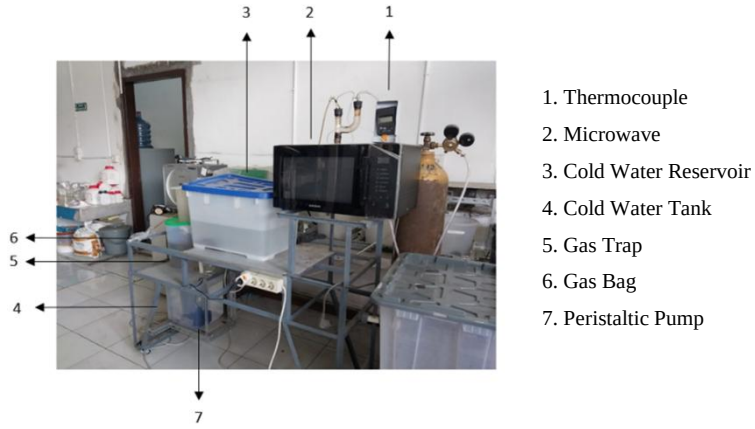


Figure 2. Assembled microwave-assisted pyrolysis equipment.

2.3. Cooling and product collection subsystem

The cooling loop comprised a cold water reservoir with a reported capacity of 47.04 L and a cold water tank with a reported capacity of 21.03 L. Pumps were used to circulate water through the cooling section to remove heat from the condensable pyrolysis vapours. The gas trap was constructed from plastic and connected to a gas bag by silicone tubing. Reported external dimension were height of 54 cm and diameter of 20 cm. This arrangement physically separated solid product which still retained inside the reactor, liquid which can be condensed and collected at downstream, and gas fraction which cannot be condensed. Figure 2 shows assembled microwave-assisted pyrolysis equipment reported in the source study.

2.4. Engineering energy indicators

For comparison at design level on specified power setting, the nominal energy of microwave given for one treatment period in 15 min were calculated based on controlled power and process time. This value represented electrical energy associated with power set point of microwave power and did not calculate power cycling, magnetron efficiency, heat losses, and also actual energy fraction absorbed by biomass. Nominal microwave energy input can be calculated by using equations 1 and 2.

$$E_{MW} = P \times t \quad (1)$$

$$e_s = \frac{E_{MW}}{m_f} \quad (2)$$

where E_{MW} is the nominal microwave energy input (kWh), P is microwave set power (kW), t is treatment time (h), e_s is nominal specific microwave energy input (kWh kg^{-1}), and m_f is feed mass (kg).

3. Results and discussion

3.1. Integrated reactor configuration

Assembled configuration integrated the functions required for microwave pyrolysis at laboratory scale in a one process sequence. Nitrogen was pumped to the upstream of microwave reactor to reduce oxygen traces before heating process started. The microwave chamber provided the electromagnetic heating environment, while thermocouple gave a signal of process temperature directly. At downstream, condensation system separated part of volatile product to liquid fraction, while the remaining gases were flowed through the gas trap to the gas bag. This modular sequence was consistent to the pyrolysis system of laboratory scale microwave, where the heating function, vapour recovery, and gas handling were treated as separated functions but still in connection each other [2], [7].

This system is particularly appropriate for pellets from empty fruit bunches since the form of pellets gave geometry and easy handling uniformly compared to loose fibrous biomass. Pellet dimension also helped to reduce variability in packing behaviour compared to untreated EFB fibers. However, absorption level of pellet in microwave depend on water content, composition, temperature, and the dielectric properties change of char layer formed during the process [3]. Therefore, direct temperature measurement is still required even power of microwave has been controlled.

3.2. Heating module and temperature monitoring

One unit of microwave has reported external dimension of 51.7 cm × 41.0 cm × 29.7 cm, chamber volume of 30 L, a maximum rated power of 1,200 W, with maximum timer setting for 6 h. Therefore, experimental power range of 450–600 W using around 37.5–50% from stated maximum power rating. The electrical supply was reported as 220 V/50 Hz. Modification by adding thermocouple was significant aspect because just power setting of microwave cannot describe the real biomass temperature. Heat generation depend on material interaction with microwave, heat losses, and changes in dielectric properties during pyrolysis process. Table 2 shows the main equipment specifications reported for the reactor system

Table 2. Main equipment specifications.

Component	Specification	Function
Microwave unit	51.7 × 41.0 × 29.73 cm; 30 L; max. 1200 W	primary heating and reactor enclosure
Thermocouple	installed in modified reactor system	process temperature monitoring
Cold-water reservoir	47.04 L	cooling water inventory
Cold-water tank	21.03 L	intermediate cooling water circulation
Gas trap	54 cm high; 20 cm diameter	downstream gas handling
Peristaltic pump	installed in cooling/process line	controlled fluid circulation
Gas bag	connected downstream of gas trap	non condensable gas collection

Previous study about microwave pyrolysis work reported that there was electrical arcing occurred at feed condition and high certain energy condition [7]. This finding was reported from the literature not from current reactor used in this experiment. Even so, this finding confirmed several practical requirement needed in designing the system, such as: metallic objects should not be present in microwave zone unless specifically designed for certain purposes, reactor need to be purged before heating process started, and power should be increased gradually only while temperature and abnormal discharge of electric are monitored.

3.3. Condensation, cooling, and gas handling

Condensation and cooling unit are the main process in separation of pyrolysis products. Two units of reported water reservoir provided total volume of water cooling of 68.07 L. The larger reservoir supports as thermal utility, while the smaller tank assists water circulation through the cooling pipe (Figure 2). Recirculation system reduces the need of cooling water in once through cooling water mode. However, actual

condenser duty cannot be calculated based on the supplied data because vapor flow rate, inlet and outlet temperature of cooling water, and condensate composition were not reported.

Gas trap and gas bag at downstream provide a certain route for non-condensable product after condensable fraction pass through cooling unit. From the experiment's point of view, this separation is useful because there is possibility to perform mass balance calculation for the next study among solid biochar, condensed bio-oil/water, and permanent gases. The present design therefore establishes the hardware required for product-fraction accounting even though complete product-yield data are not available in the reported results.

3.4. Operating Envelope and Nominal Microwave Energy Input

Nominal microwave energy input calculated for the reported 15 min treatment time are shown in Table 3. While nominal microwave energy input as a function of set power for the reported 15-min treatment period are shown on Figure 3. The nominal energy supplied over 15 min increased linearly from 0.1125 kWh at 450 W to 0.1500 kWh at 600 W. Across the stated feed-mass range, the corresponding nominal specific microwave input spans 0.45-1.50 kWh kg-1. The wide specific-energy range results from varying both power and biomass loading. Consequently, interpreting biochar yield or quality only against microwave power could be misleading if feed mass is changed at the same time; specific energy input provides a more informative engineering basis for comparing operating conditions.

Table 3. Nominal microwave energy input calculated for the reported 15 min treatment time.

Power (W)	Energy per batch (kWh)	Specific energy at 100 g (kWh kg^{-1})	Specific energy at 250 g (kWh kg^{-1})
450	0.1125	1.125	0.450
500	0.1250	1.250	0.500
550	0.1375	1.375	0.550
600	0.1500	1.500	0.600

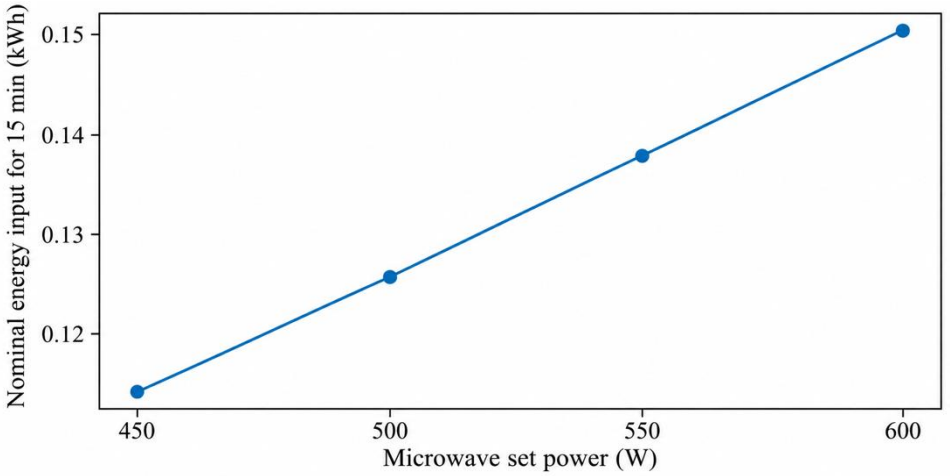


Figure 3. Nominal microwave energy input for 15 min treatment period.

These calculated values are not measurements of energy efficiency. Actual absorbed energy will be lower than nominal electrical power input and will depend on microwave duty cycling, reflected power, energy losses in microwave chamber, sensible heating in reactor hardware, vaporisation process, reaction enthalpy, and heat losses to the environment. Therefore, next experiment should record the actual electrical energy consumption, temperature versus time profile, and mass yield of product, energy efficiency and carbon conversion performance can be calculated quantitatively.

3.5. Implications for biochar production and scale-up

This design provides a useful laboratory platform to study how microwave power and biomass affect EFB conversion. The planned characterization method such as: biochar yield, water content, volatile matter, bulk density, calorific value, SEM and FTIR, are appropriate to connect operation condition of reactor with product

amount, proximate properties, morphology, and functional group. Previous research showed that temperature, heating rate, interaction between microwave and material significantly affect biochar characteristic [1]–[5].

For scale up process, to maintain the ratio of nominal power to same mass, cannot guarantee obtaining the equivalent performance, because the depth of microwave penetration, cavity field distribution, reactor geometry, vapour releasing, and heat dissipation will change with the increasing of scale. For the bigger system required special evaluation to electromagnetic field uniform, reactor material, gas tightness, condenser duty, pressure control, and safety interlocks. Therefore, the used equipment in this research is concluded as laboratory scale platform with controlled parameter studies rather that a direct industrial prototype.

4. Conclusion

A laboratory scale microwave assisted with pyrolysis system was designed and assembled for conversion of EFB pellets to biochar. The process sequence integrates a modified microwave heating chamber, nitrogen purge, thermocouple, vapor condensation unit, recirculating cooling water system, gas trap, and gas bag. The reported operating condition comprises 450-600 W microwave power, 100-250 g biomass charge, and a 15-min treatment time. The nominal microwave energy input is 0.1125-0.1500 kWh per batch, corresponding to 0.45-1.50 kWh kg^{-1} across the stated feed-mass range. The configuration provides the essential unit operations needed to separate solid, condensable, and gaseous pyrolysis products and supports systematic investigation of microwave power and loading effects. Further evaluation should combine actual power consumption, temperature time histories, complete product mass balances, and the planned biochar characterization measurements before conclusions are drawn regarding optimum yield, energy efficiency, or biochar quality.

Conflict of interest

The authors declare no conflict of interest.

References

[1] A. Li, H.-L. Liu, H. Wang, H.-B. Xu, L.-F. Jin, J.-L. Liu, and J.-H. Hu, "Effects of temperature and heating rate on the characteristics of molded bio-char," *BioResources*, vol. 11, pp. 3259-3274, 2016, doi: 10.15376/biores.11.2.3259-3274.

[2] D. R. Nhuchhen, M. T. Afzal, T. Dreise, and A. A. Salema, "Characteristics of biochar and bio-oil produced from wood pellets pyrolysis using a bench scale fixed bed, microwave reactor," *Biomass and Bioenergy*, vol. 119, pp. 293-303, 2018, doi: 10.1016/j.biombioe.2018.09.035.

[3] A. A. Salema, F. N. Ani, J. Mouris, and R. Hutcheon, "Microwave dielectric properties of Malaysian palm oil and agricultural industrial biomass and biochar during pyrolysis process," *Fuel Processing Technology*, vol. 166, pp. 164-173, 2017, doi: 10.1016/j.fuproc.2017.06.006.

[4] G. Kabir, A. T. Mohd Din, and B. H. Hameed, "Pyrolysis of oil palm mesocarp fiber and palm frond in a slow-heating fixed-bed reactor: A comparative study," *Bioresource Technology*, vol. 241, pp. 563-572, 2017, doi: 10.1016/j.biortech.2017.05.180.

[5] M. A. Hossain, J. Jewaratnam, P. Ganesan, J. N. Sahu, S. Ramesh, and S. C. Poh, "Microwave pyrolysis of oil palm fiber (OPF) for hydrogen production: Parametric investigation," *Energy Conversion and Management*, vol. 115, pp. 232-243, 2016, doi: 10.1016/j.enconman.2016.02.058.

[6] A.R. Ilhamsyah, Characterization of Pyrolysis Products of Empty Palm Oil Bunches and Biopellets of Empty Palm Oil Bunches, *Institut Pertanian Bogor*, Bogor, Indonesia, 2015.

[7] T. Haeldermans et al., "Microwave assisted and conventional pyrolysis of MDF - Characterization of the produced biochars," *Journal of Analytical and Applied Pyrolysis*, vol. 138, pp. 218-230, 2019, doi: 10.1016/j.jaap.2018.12.027.

[8] I. Sari, U. I. Purnamasari, and M. T. Lubis, "Production of activated carbon from Zalacca peel (*Salacca zalacca*) by physical process using steam assisted microwave heating," *Jurnal Teknik Kimia USU*, vol. 6, pp. 45-49, 2017, doi: 10.32734/jtk.v6i4.1598.

[9] N. Hastuti, G. Pari, D. Setiawan, Mahpudin, and Saepuloh, "Charcoal quality of six types of wood from West Java as dry distillation products," *Jurnal Penelitian Hasil Hutan*, vol. 33, pp. 337-346, 2015, doi: 10.20886/jphh.2015.33.4.337-346.

[10] A. Kurniawan, B. Haryono, M. Baskara, and Y. T. Setyono, "The effects of biochar application to planting media on the growth of sugarcane seeds (Saccharum officinarum L.)," *Jurnal Produksi Tanaman*, vol. 4, pp. 153-160, 2016, doi: 10.21176/protan.v4i2.273.