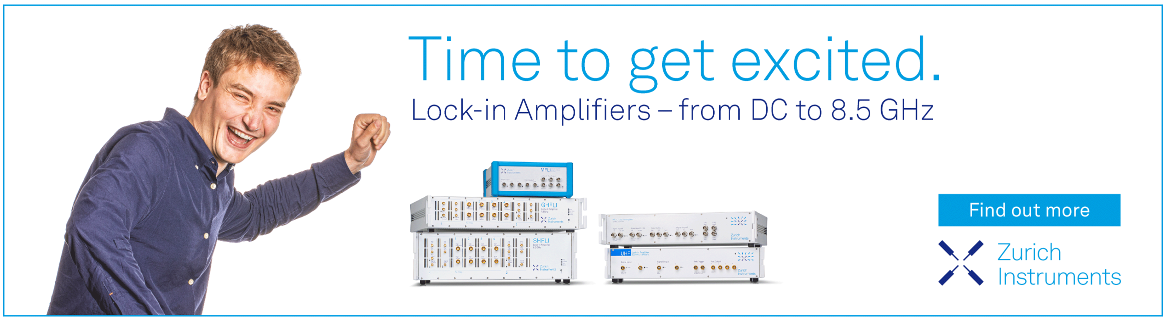
RESEARCH ARTICLE | APRIL 25 2023

Microwave torrefaction technology in biochar production: A review

Muhammad Agung; Ismail Rahim ✉; Faizal Amir

AIP Conference Proceedings 2630, 020011 (2023)
https://doi.org/10.1063/5.0125902



Microwave Torrefaction Technology in Biochar Production: A Review

Muhammad Agung[1,a)], Ismail Rahim[2,b)], and Faizal Amir[2,c)]

[1] *Mechanical Vocational Technology Education, Faculty of Engineering, Universitas Negeri Makassar, Indonesia*
[2] *Automotive Vocational Technology Education, Faculty of Engineering, Universitas Negeri Makassar, Indonesia*

[a)] agung@unm.ac.id
[b)] Corresponding author: ismail_rahim@unm.ac.id
[c)] faizalamir64@unm.ac.id

Abstract. Torrefaction is a thermochemical process in an inert or limited oxygen environment where biomass is slowly heated to a specified temperature range. The art of torrefaction has caught the attention of power industries to produce biochar and coal substitute from biomass. In recent years, there has been an increasing interest in torrefaction technology. The main difference between technologies is the reactor design and the heating mode. These parameters influence the product quality of torrefied biomass. Microwave torrefaction is one of the available technologies that recently received considerable attention due to some advantages. Along with this growth, there is increasing concern over comparing microwave torrefaction with conventional ones. So far, there has been little discussion about the technical comparison of reactor design of microwave torrefaction itself. This paper will review the research conducted on the microwave design of biomass torrefaction. The use of microwave as an apparatus for torrefaction process reported is mainly dominated by domestic microwave oven followed by the single-mode microwave oven, non-modified microwave oven and only a few studies of large-scale microwave reactor. Each type of microwave reactor design determines mass yield, energy density, and energy yield as quality parameters of torrefied biomass. The findings should contribute to the field of a microwave as an apparatus for torrefaction technology.

BACKGROUND

Biomass energy accounts for many resources around the world. It also becomes a most promising energy source. Biomass covers a broad spectrum: from tiny grass to massive trees, from small insects to large animal wastes, and the products derived from these. Indonesia's biomass potential is reported around 59GWe, most of which comes from the agricultural sector crops plantation. Data from the ministry of agriculture, crops production is dominated by palm oil, followed by rubber and coconut. Paddy, Maize, and Cassava also shows the highest production[1]

Biomass primarily consists of cellulose, hemicellulose, lignin, and other compounds such as proteins, sugars and salts, starches, water, hydrocarbons, and ash. The composition of these constituents in the biomass varies with species, age, growth location, and growth conditions.

The primary thermal biomass conversion techniques are combustion, gasification, pyrolysis, and torrefaction. Torrefaction is a pretreatment method for upgrading biomass as a solid fuel for further use instead of direct use in its raw form. It is a thermochemical process in an inert or limited oxygen environment. Primarily, torrefaction is characterized by hemicellulose degradation, but other polymers, cellulose, and lignin, also degrade to some extent that depends on the temperature. In the torrefaction process, biomass is slowly heated at a specified temperature and time until degradation of its hemicellulose content

Torrefied biomass has some advantages, including lower moisture, good hydrophobicity, improved grind ability, higher energy density, mass density, and heating value, also reducing O/C ratio[2]. Torrefied biomass finds use in fields such as a substitute for coke in blast furnaces, cofiring with coal in coal-fired power plant boilers, convenient

Proceeding of International Conference on Energy, Manufacture, Advanced Material and Mechatronics 2021
AIP Conf. Proc. 2630, 020011-1–020011-6; https://doi.org/10.1063/5.0125902
Published by AIP Publishing. 978-0-7354-4453-9/$30.00

fuel for gasification, potential feedstock for chemical industries, and as a fuel in the decentralized or residential heating system.

TORREFACTION TECHNOLOGY

Biomass torrefaction was first introduced as an alternative fuel to petroleum in the 20th century in France. In the early 1980s, the first torrefaction industrials scale was implemented, and its design consist of two types: continuous or batch process[3]. The continuous process operated wherein heat transfer takes place by conduction through the contact of the biomass with the heated surfaces of the reactor while the batch process is characterized by heat transfer produced by the convection of the combustion gas from biomass.

Torrefaction technology is continuing to evolve in recent years by improving the reactor and combining heating and mixing modes. There is two common heating mode applied in the torrefaction process: indirectly and directly heating. For Indirectly mode, the heat does not contact biomass for example in rotating drum and screw conveyer reactors. A rotary drum reactor is designed to dry the biomass which combines the function of cooling and drying with an energy saving of 30-50%. In the Screw conveyor torrefaction concept, the heat required is generated by the combustion of the gases that are released in the process. For this purpose, the gases are directed to a dedicated combustion chamber, in which the combustion takes place at sufficiently high temperatures[4]. Rotating packaged bed on bamboo torrefaction was investigated with varying rotating speed and temperature[5]. The results suggest that torrefaction in a rotating packed bed is an efficient process to upgrade biomass for producing a green and sustainable alternative to coal utilized in industry. Torrefaction of the macroalga was carried out using a vertical tubular reactor. This apparatus allows torrefaction to take place at an extremely low temperature [6]

Directly mode usually uses hot gas, hot solid, superheated steam as a heating media. Hydrothermal reactors, fluidized beds, and microwaves are included in this type. In the hydrothermal reactor, torrefaction proceeds at a temperature range of 180 °C to 280 °C in the presence of subcritical liquid water, so the product is usually mentioned as "hydrochar". Properties of bio "hydrochar' produced from peat were observed using hydrothermal process. It was found that the maximum heating value was determined for hydrochar obtained at 230 °C (28.03 MJ/kg for HHV and 26.77 MJ/kg for LHV). Compared to the original peat, the index for hydrochar at 210 °C is 9 times higher and contained fewer inorganic elements that are partially dissolved in water[7]. Biochar produced from Camellia shells obtained from hydrothermal torrefaction has been compared to biochar produced from dry torrefaction. Hydrothermally prepared biochar had stable energy and mass yield with temperature than dry torrefaction and its coalification status is similar to that of sub-bituminous coal [8]. A hydrothermal torrefaction experiment was performed to produce hydro-char of Azolla biomass at a high-pressure autoclave. Torrefied sample showed a significantly higher degree of decomposition rather than conventional torrefaction and contained a negligible number of substances of lower thermal stability up to 250–280 °C, while the decomposition of hydrochars started at much lower temperatures (below 200 °C) [9].

Several studies have reported a torrefaction process using a fluidized bed reactor due to its excellent gas–solids heat and mass transfer performance. Torrefaction of sawdust was conducted in a bench fluidized bed with an inclined orifice distributor, to create a vortex motion of particles in the bed. The higher heating values and the hydrophobicity of torrified sawdust were confirmed to increase in this experiment [10]. The performance of torrefaction treatment of biomass pellet using fluidized bed reactor was investigated using air as a carrier gas. Results of this work revealed that no crack was detected during the thermal treatment and the bonds formed during pelletization are quite well [11].

MICROWAVE TORREFACTION TECHNOLOGY

A considerable amount has been published about the comparison of conventional torrefaction and microwave torrefaction. Conventional torrefaction is practiced in a tube furnace with a quartz tube powered by electricity. The reaction temperature can be controlled precisely but a longer duration is required[12]. Microwave torrefaction involves heating assisted by electromagnetic irradiation creates an extremely fast rating of the biomass interior, a matter of seconds, and has a highly tunable heating rate[3]. Several studies have revealed some advantages of microwave heating in the torrefaction process such as rapid, selective, and non-contact heating, abrupt start and stop automation, and a high level of safety[14].

Microwave heating processing has attracted attention since it satisfies many requirements of green chemistry. It has a fast-processing time compared to another heating system which decreases energy consumption, averts the use of solvents, separation agents, or other auxiliary chemicals, does not generate smoke and waste in the processing step, and is easy to operate. Microwave processing also has fast heat transfer since the heat is produced directly from inside the material, leading to better heat transfer, and substantially it has a higher energy yield compared to conventional ovens which transmit heat by conduction-convection.

The previous study reviewed the works of literature as shown in figure 1, on microwave heating apparatus and reported that it was dominated by modified domestic microwave ovens of about 52%, single-mode and multi-mode microwave ovens around 22%, non-modified microwave ovens 19% and around 7% of large or industrial scale[15]. The comparison of microwave torrefaction and conventional torrefaction on process energy, volatile energy and produced bio-energy is shown in figure 1.

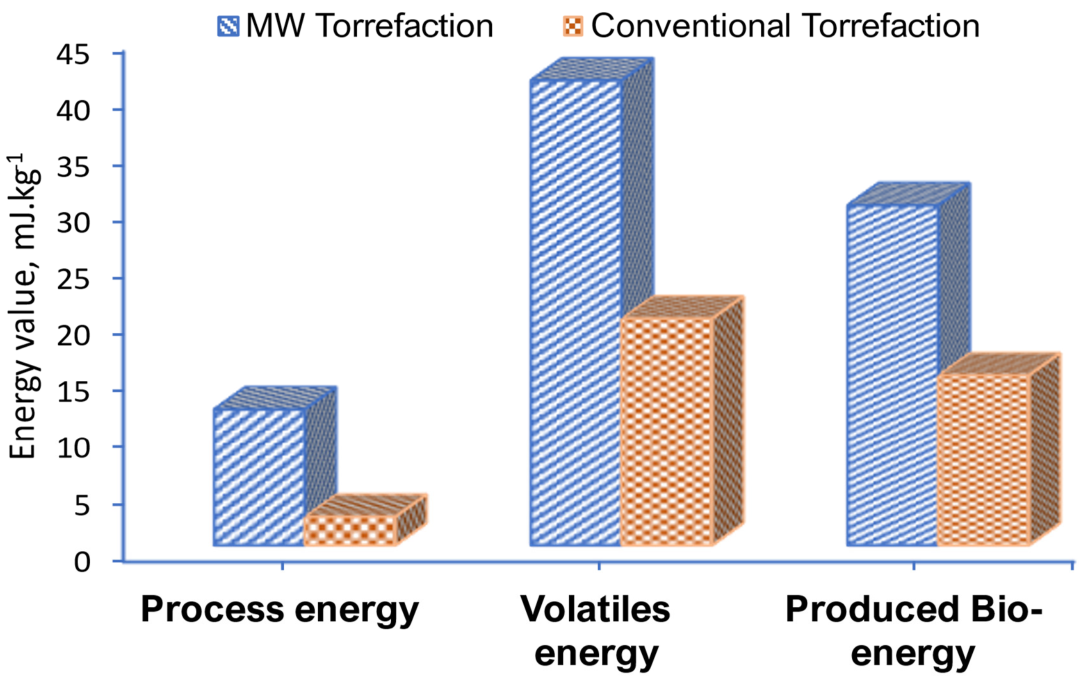


FIGURE 1. The comparison of microwave torrefaction and conventional torrefaction

Modified Microwave Oven

Several studies have reported modification of microwaves for biomass treatment. It was mainly using a conventional microwave oven modified with a cylindrical reactor put inside the microwave oven. These studies reported different parameters that influenced a feedstock material processing result, such as microwave power, temperature, and processing time [6] [7] [18]. Some of them use nitrogen as a purging gas to ensure an inert atmosphere.

Microwave equipment consists of four main parts: magnetron, cavities, waveguide, and applicator. Modification of these parts was conducted in many applications for biomass torrefaction.

Torrefaction of *Leucaena*, rice straw, and *Pennisetum* was investigated using a single-mode microwave oven with 2.45 GHz frequency[19], [20]. A quartz tube was placed in the pathway of microwaves and nitrogen was purged to maintain non-oxidative conditions. The use of nitrogen as non-oxidative purging gas in the torrefaction process incurs higher processing costs. However, it was reported that torrefaction products produced from non-oxidative torrefaction retained higher H and lower O than obtained from oxidative torrefaction[21].

Effect of microwave power level and processing time was investigated in the torrefaction of biomass from the agricultural residue of wheat straw and *Mischantus Gigantius*. A 2.45 GHz of microwave oven was used with some modifications. The reactor was put inside a microwave oven which has three ports, first for nitrogen purging, second for K-type thermocouple, and third for exhaust gases. Specific microwave power levels were reported for the tested biomass. Power level is suggested to be 320 W and torrefaction with processing time around 20-30 min to improve the fuel characteristics like O/C, H/C, HHV, energy density of the tested biomass[17].

A typical microwave torrefaction apparatus was reported at low torrefaction temperature (160ºC, 170ºC, and 180ºC) using microalga *Chlorella Vulgaris* ESP-31 as biomass. Torrefaction was conducted as a wet torrefaction that uses hydrothermal media or hot compressed water. The solid yield decreases with increasing either wet torrefaction temperature or time. The solid yield decreases from 61.68% to 52.58% for the temperature increasing from 160ºC to 180ºC.[16]

Single-Mode/Multi-Mode Microwave Oven

Single-mode microwave focused targeted the microwaves through a waveguide to reach biomass. It has a specific width as a requirement by wavelength to increase the effectiveness of radiation. It has a simple design with the advantage of directing the wave to the biomass. Multi-mode microwave reactors possess a larger cavity in relation with the wavelength and biomass Microwaves coming into the cavity are reflected on the walls and repeatedly bounce before passing into the product, this phenomenon usually happens over a thousand times in a domestic oven, increasing a reflection mode that avoids the wave's orientation into the sample.

Microwave torrefaction of *Leucaena* was carried out by using a single-mode microwave oven which operates at the frequency of 2.45 GHz. A microwave power level designated at 100, 150, 200, and 250 W with processing time was set at 15, 20, 25, and 30 min. The effects of microwave power level on HHV and energy yield were 1.6 and 2.5 times higher than those of processing time, respectively[22].

Non-Modified Microwave Oven

The microwave oven has a higher energy yield compared to conventional ovens which transmit heat by conduction-convection[23]. This makes a microwave oven can be directly used without any modification. A bench top microwave convection oven with 2.45 GHz was used as a torrefaction apparatus for wheat and barley straw. Barley straw was observed to carbonize more under microwave irradiation and the H/C and O/C ratio decreases with an increase in power and reaction time. The energy density, mass, and energy yield were also reported to increase for both wheat and barley straw [24]. Microwave heating of canola residue was investigated with microwave power variation. Properties such as proximate and ultimate analysis density and energy content were confirmed very close to coal signifying its potential for solid fuel application[9].

Large/Industrial Scale

The application of torrefaction technology on an industrial scale has been widely reported in various studies. However, raising the scale from a laboratory to a large or industrial scale needs further studies. A dual-scale wood torrefaction model was developed for industrial configuration. This model is used to investigate the effect of the stack configuration on the heat treatment of the boards. Results concluded that emphasis should be given to dealing with moisture, considering water evaporation, and predicting temperature overshoot [25] Russian Academy of Science proposed a new scheme of industrial torrefaction technology, including a gas piston engine. The torrefied pellets have similar properties with low-grade brown coal [26]. A pilot-industrial scale of a torrefied biomass pellet production unit was built in Portugal in 2013. The rotary drum torrefaction reactor with indirect heating biomass was applied in this project with a theoretical production capacity of 720 kg/h of torrefied biomass[27]

CONCLUSION

Due to its specific characteristics, microwave torrefaction has become a promising technology applied for biomass treatments. Various applications of torrefaction technology both on a laboratory scale and on an industrial scale have been reported to produce products that have adequate properties for solid fuel. Microwave torrefaction as advanced heating technology results from analysis combination and techniques to deliver a sustainable, economic, and versatile process. Therefore, it can be recommended as a technological option in fuel production.

REFERENCES

1. R. Case, "Renewable energy potential and future.pdf," no. April, pp. 44–52, 2016.
2. Y. Niu *et al.*, "Biomass torrefaction: properties, applications, challenges, and economy," *Renewable and Sustainable Energy Reviews*, vol. 115, no. August, p. 109395, 2019, doi: 10.1016/j.rser.2019.109395.
3. L. J. R. Nunes, J. C. de Oliveira Matias, and J. P. da Silva Catalão, "Torrefaction Technologies," *Torrefaction of Biomass for Energy Applications*, pp. 161–172, 2018, doi: 10.1016/B978-0-12-809462-4.00006-7.
4. Y. Sun, J. Jiang, S. Zhao, Y. Hu, and Z. Zheng, "Review of torrefaction reactor technology," *Advanced Materials Research*, vol. 347–353, pp. 1149–1155, 2012, doi: 10.4028/www.scientific.net/AMR.347-353.1149.
5. W. H. Chen, M. K. Pillejera, and M. D. de Luna, "Influence of reactor rotating speed on bamboo torrefaction," *Energy Procedia*, vol. 142, pp. 131–135, 2017, doi: 10.1016/j.egypro.2017.12.021.
6. Y. Uemura, R. Matsumoto, S. Saadon, and Y. Matsumura, "A study on torrefaction of Laminaria japonica," *Fuel Processing Technology*, vol. 138, pp. 133–138, 2015, doi: 10.1016/j.fuproc.2015.05.016.
7. K. Krysanova, A. Krylova, and V. Zaichenko, "Properties of biochar obtained by hydrothermal carbonization and torrefaction of peat," *Fuel*, vol. 256, no. July, p. 115929, 2019, doi: 10.1016/j.fuel.2019.115929.
8. R. Tu, E. Jiang, S. Yan, X. Xu, and S. Rao, "The pelletization and combustion properties of terrified Camellia shell via dry and hydrothermal torrefaction: A comparative evaluation," *Bioresource Technology*, vol. 264, pp. 78–89, 2018, doi: 10.1016/j.biortech.2018.05.009.
9. B. Babinszki *et al.*, "Comparison of hydrothermal carbonization and torrefaction of azolla biomass: Analysis of the solid products," *Journal of Analytical and Applied Pyrolysis*, vol. 149, no. May, p. 104844, 2020, doi: 10.1016/j.jaap.2020.104844.
10. [10] H. Li, X. Liu, R. Legros, X. T. Bi, C. J. Lim, and S. Sokhansanj, "Torrefaction of sawdust in a fluidized bed reactor," *Bioresource Technology*, vol. 103, no. 1, pp. 453–458, 2012, doi: 10.1016/j.biortech.2011.10.009.
11. P. Brachi, R. Chirone, M. Miccio, and G. Ruoppolo, "Fluidized bed torrefaction of biomass pellets: A comparison between the oxidative and inert atmosphere," *Powder Technology*, vol. 357, pp. 97–107, 2019, doi: 10.1016/j.powtec.2019.08.058.
12. M. J. Gronnow *et al.*, "Torrefaction/biochar production by microwave and conventional slow pyrolysis - comparison of energy properties," *GCB Bioenergy*, vol. 5, no. 2, pp. 144–152, 2013, doi: 10.1111/gcbb.12021.
13. S. H. Ho, C. Zhang, W. H. Chen, Y. Shen, and J. S. Chang, "Characterization of biomass waste torrefaction under conventional and microwave heating," *Bioresource Technology*, vol. 264, no. May, pp. 7–16, 2018, doi: 10.1016/j.biortech.2018.05.047.
14. P. D. Patil *et al.*, "Power dissipation in microwave-enhanced in situ transesterification of algal biomass to biodiesel," *Green Chemistry*, vol. 14, no. 3, pp. 809–818, 2012, doi: 10.1039/c2gc16195h.
15. M. A. H. Mohd Fuad, M. F. Hasan, and F. N. Ani, "Microwave torrefaction for viable fuel production: A review on theory, affecting factors, potential and challenges," *Fuel*, vol. 253, no. May, pp. 512–526, 2019, doi: 10.1016/j.fuel.2019.04.151.
16. Q. V. Bach, W. H. Chen, S. C. Lin, H. K. Sheen, and J. S. Chang, "Wet torrefaction of microalga Chlorella vulgaris ESP-31 with microwave-assisted heating," *Energy Conversion and Management*, vol. 141, pp. 163–170, 2017, doi: 10.1016/j.enconman.2016.07.035.
17. M. Kosowska-Golachowska, A. Magdziarz, P. Janus, and D. Urbaniak, "Experimental study on microwave torrefaction of lignocellulosic biomass," *E3S Web of Conferences*, vol. 154, 2020, doi: 10.1051/e3sconf/202015402008.
18. N. Amaliyah and A. E. Eka Putra, "Microwave-assisted pyrolysis of cashew nut shell," *International Journal of Design and Nature and Ecodynamics*, vol. 16, no. 2, pp. 227–232, 2021, doi: 10.18280/ijdne.160213.
19. Y. F. Huang, P. H. Cheng, P. te Chiueh, and S. L. Lo, "Microwave Torrefaction of leucaena to Produce Biochar with High Fuel Ratio and Energy Return on Investment," *Energy Procedia*, vol. 105, pp. 35–40, 2017, doi: 10.1016/j.egypro.2017.03.276.
20. Y. F. Huang, W. R. Chen, P. T. Chiueh, W. H. Kuan, and S. L. Lo, "Microwave torrefaction of rice straw and pennisetum," *Bioresource Technology*, vol. 123, pp. 1–7, 2012, doi: 10.1016/j.biortech.2012.08.006.
21. K. M. Lu, W. J. Lee, W. H. Chen, S. H. Liu, and T. C. Lin, "Torrefaction and low temperature carbonization of oil palm fiber and eucalyptus in nitrogen and air atmospheres," *Bioresource Technology*, vol. 123, pp. 98–105, 2012, doi: 10.1016/j.biortech.2012.07.096.

22. Y. F. Huang, P. H. Cheng, P. te Chiueh, and S. L. Lo, "Leucaena biochar produced by microwave torrefaction: Fuel properties and energy efficiency," *Applied Energy*, vol. 204, pp. 1018–1025, 2017, doi: 10.1016/j.apenergy.2017.03.007.
23. A. Aguilar-Reynosa, A. Romaní, R. Ma. Rodríguez-Jasso, C. N. Aguilar, G. Garrote, and H. A. Ruiz, "Microwave heating processing as alternative of pretreatment in second-generation biorefinery: An overview," *Energy Conversion and Management*, vol. 136, pp. 50–65, 2017, doi: 10.1016/j.enconman.2017.01.004.
24. S. K. Satpathy, L. G. Tabil, V. Meda, S. N. Naik, and R. Prasad, "Torrefaction of wheat and barley straw after microwave heating," *Fuel*, vol. 124, pp. 269–278, 2014, doi: 10.1016/j.fuel.2014.01.102.
25. P. Perré, R. Rémond, and I. Turner, "A comprehensive dual-scale wood torrefaction model: Application to the analysis of thermal run-away in industrial heat treatment processes," *International Journal of Heat and Mass Transfer*, vol. 64, pp. 838–849, 2013, doi: 10.1016/j.ijheatmasstransfer.2013.03.066.
26. J. S. Kuzmina, G. A. Sytchev, and V. M. Zaychenko, "Torrefaction. Prospects and application," *Chemical Engineering Transactions*, vol. 50, pp. 265–270, 2016, doi: 10.3303/CET1650045.
27. L. J. R. Nunes, "A case study about biomass torrefaction on an industrial scale: Solutions to problems related to self-heating, difficulties in pelletizing, and excessive wear of production equipment," *Applied Sciences (Switzerland)*, vol. 10, no. 7, 2020, doi: 10.3390/app10072546.