Terbit *online* pada laman web jurnal : http://metal.ft.unand.ac.id

METAL: Jurnal Sistem Mekanik dan Termal

| ISSN (Print) 2598-1137 | ISSN (Online) 2597-4483 |

Research Article

Pyrolytic Product Distribution Analysis on Co-Pyrolysis of Face Mask Waste and Lignocellulosic Waste

Rain Agri Mahendra[a], Abrar Ridwan[a], Wahyu Meka[b], Yulia Fitri[c], Tri Nur Rezeki[a], Azzalya Putri Athala[c], Laras Sita Widara[c], Munawir Hamzah[c]*

[a]*Faculty of Engineering, Universitas Muhammadiyah Riau, Pekanbaru, 28294, Indonesia*
[b]*Department of Chemical Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, 60111, Indonesia*
[c]*Faculty of Mathematics, Natural Science, and Health, Universitas Muhammadiyah Riau, Pekanbaru, 28294, Indonesia*

INFORMASI ARTIKEL

Article History:
Received: 12 August 2023
Revised: 25 September 2023
Accepted: 29 October 2023

KATA KUNCI

Co-pyrolysis
Face Mask
Lignocellulose
Biofuel
Biochar

KORESPONDENSI

E-mail: w.meka@its.ac.id

A B S T R A C T

Co-pyrolysis was conducted at 400 °C with N_2 flowing at 0.5 l/min on face mask and lignocellulosic waste to investigate synergy-dependant pyrolytic product yields. The lignocellulosic waste used was the most generated biomass waste such as food waste, garden waste, and paper. Individually, food waste pyrolysis generated the highest amount of pyrolytic oil yield (40%) due to high content of starch degraded at low temperatures while pyrolysis of garden waste and paper generated lower pyrolytic liquid yields at around 15% because high content of lignin degraded at high temperatures. No pyrolytic liquid was observed in face mask pyrolysis due to consecutive degradation of long-chain aliphatic compounds and repolymerisation of the degraded compounds into wax products. Co-pyrolysis of face masks and lignocellulosic waste with proportion of 25:75 was able to improve pyrolytic yields with food waste as the lignocellulosic waste giving the highest yield of pyrolytic liquid. The presence of food waste suppressed the formation of wax products because of starch domination. Oxygen donor from the starch to the aliphatic compounds of face mask might enhance oxygenated compound yields indicated with large pyrolytic liquid yield at 40% and decreased char yield.

1. INTRODUCTION

Coronavirus Disease 2019 (COVID-19) had been a seriously deadly pandemic for the last couple years that it caused breathing disturbance problems, pneumonia, and death [1-2]. Personal protective equipment such as face masks and medical gloves was used as non-pharmaceutical intervention to cut the spreading of COVID-19 [3] In Indonesia, the use of face mask was mandatory as per government's instruction to suppress surging COVID-19 [4-5]. Due to health issues, face mask waste is not plausible to recycle and become another source of COVID-19 spread. The inability to recycle face mask waste along with poor waste management promoted the increase of medical waste [6]. Up until August 2021, Indonesian medical waste had reached around 20,000 t m^{-3} [7]. Medical waste does not only contain hazardous waste (B3) but also non-hazardous waste (B3) composed of domestic waste such as food waste, papers, and garden waste in significant proportions [8-11].

https://doi.org/10.25077/metal.7.2.23-30.2023

The amount of waste in Indonesia in 2021 was around 28 million tonnes, 35.68% (10 million tonnes) of which were improperly managed [12]. The accumulation of such amount might potentially damage the environment due to its hazardous substance [13]. To reduce the waste generation rate, a proper method is required. One of such method is pyrolysis which is considered environmentally-friendly and highly efficient [14].

Pyrolysis is a thermal material decomposition process without O_2 or with a very low amount of O_2 at relatively low temperatures, 400 to 700 °C. The pyrolysed materials are expected to degrade into oil, char, and gas [14-22]. Furthermore, pyrolytic product qualities could be enhanced via co-pyrolysis two or more different materials, e.g., biomass and plastics. The presence of plastics in the co-pyrolysis enhances the quality and yield of the products because of high C and H content and low O content that the co-pyrolysis facilitates H donor to the biomass to form H-rich hydrocarbons [23]. Compared to other methods, e.g., hydrodeoxygenation, hydrogenation, etc., co-pyrolysis is relatively safe since it does not require high pressures [24-29].

Hence, this paper aims to investigate the influence of co-pyrolysis of face masks as hazardous medical waste and food waste, papers, and garden waste as non-hazardous medical waste on the yield of pyrolytic oil, char, and wax. This paper further is expected to contribute as an approach to promote the use of alternative fuel and waste reduction.

2. METODOLOGY

2.1. Materials

The co-pyrolysis of medical waste conducted in the laboratory of Chemical Engineering Study Programme at Universitas Muhammadiyah Riau. The hazardous medical waste was disposable face masks purchased in local pharmacies in Pekanbaru. The non-hazardous medical waste was food waste, garden waste, and papers. The food waste was obtained from local Padang restaurants in Pekanbaru. The garden waste was garden residues collected at the yard of Universitas Muhammadiyah Riau. The papers were obtained from paper bins located in the office buildings at Universitas Muhammadiyah Riau. The medical waste was converted into samples with particle sizes of roughly 50 mm via milling to reduce intra-material heat and mass transfer limitation [30-31]. The food waste samples were dried at 90 °C for 24 hours to remove excessive moisture before co-pyrolysed [32].

2.2. Experimental Setup

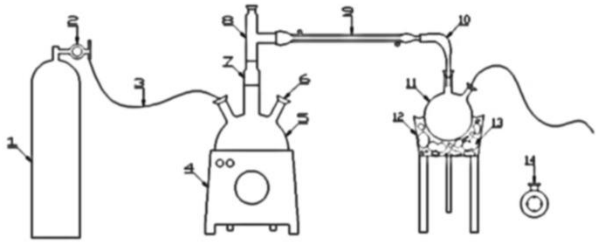

Figure 1. Pyrolysis System Setup: (1) Nitrogen Gas Cylinder, (2) Regulator, (3) Hose, (4) Heating Mantle, (5) Three-neck Round-bottom Flask, (6) Rubber Stopper, (7) Reducer, (8) T-neck, (9) Liebig Condenser, (10) Vacuum Adapter, (11) Two-neck Round-bottom flask, (12) Cooling Bath, (13) Salted Ice, (14) Stopwatch

The pyrolysis equipment diagram is illustrated in Figure 1. Each prepared sample was put in the three-neck round-bottom flask. During pyrolysis, N_2 was allowed to flow at roughly 1 min^{-1} from the gas cylinder to the three-neck round-bottom flask to ensure O_2-free environment and efficient heat transfer via forced convection [33-34]. Pyrolysis duration was started when the heating mantle was turned on and monitored via a stopwatch. The maximum set point of heating mantle temperature was at 400 °C. The produced gas flowed through Liebig condenser and condensed counter-currently using flowing tap water. The condensed gas flowed through the Liebig condenser and were collected in the two-neck round-bottom flask. The two-neck round-bottom flask was immersed in an ice bucket to keep the two-neck round-bottom flask environment at water freezing temperature reducing pyrolytic fluid flow velocity to allow more pyrolytic liquid aerosol left in the two-neck round-bottom flask [35]. The observed time shown on the stopwatch was stopped when the gas flowing in the pyrolysis equipment was already clear from smoke. The obtained pyrolytic liquid was weighed after pyrolysis.

Yield percentage of pyrolytic oil obtained from the co-pyrolysis is calculated via Equation 1.

$$L = \frac{m_2}{m} \times 100 \quad (1)$$

Yield percentage of pyrolytic char obtained from the co-pyrolysis is calculated via Equation 2.

$$S = \frac{m_3}{m} \times 100 \quad (2)$$

Yield percentage of pyrolytic gas obtained from the co-pyrolysis is calculated via Equation 3.

$$G = \frac{m - m_2 - m_3 - m_4}{m} \times 100 \quad (3)$$

Yield percentage of pyrolytic wax obtained from the co-pyrolysis is calculated via Equation 4.

$$W = \frac{m_4}{m} \times 100 \quad (4)$$

3. RESULT AND DISCUSSION

3.1. Raw Material Characteristics

Raw materials used in this research were face masks as the hazardous medical waste and food waste, garden waste, and papers as the non-hazardous medical waste. The face masks were made of several polymers, namely: mask filter made of polypropylene, ear loop made of polyamide and polyurethane, and nose wire made of aluminium [5], [36]. The food waste consisting of rice, meats, bones, and vegetables, were chemically a combination of starch, hemicellulose, cellulose, lipid, and protein [37]. Papers and garden waste contained lignin, hemicellulose, and cellulose [38-40]. Based on their primary compositions, these raw materials were rich in C, H, and O, which are very potential as sources of alternative energy. The percentage of these compositions is reflected in both proximate analysis results as shown in Table 1.

Table 1. Proximate Analysis Result

Waste	Moisture (%)	Volatile (%)	Ash (%)	Fixed Carbon (%)
Face Mask	2,24	63,85	15,38	18,52
Food Waste	26,95	70,06	2,51	0,47
Garden Waste	6,95	64,11	24,15	4,77
Paper	3,02	65,54	19,20	12,23

3.2. The Influence of Particle Sizes and Temperatures

Particle size affects the performance of co-pyrolysis. Heating rates in the three-neck round-bottom flask were faster as particle sizes became smaller due to less heat and mass transfer restriction within the raw materials [31]. Fast heating rates promotes fast pyrolysis rate which influences pyrolytic product selectivity [41].

Temperatures also significantly dictates the selectivity of pyrolytic product yield [40,42-46]. Each of medical waste component also behaves uniquely when pyrolysed at certain temperatures [47]. High temperatures enhance carbon conversion and heavy molecule breakdown [18,48]. The enhanced carbon conversion is the results of fast heating rates promoted via high temperatures. Moderately fast heating rates accommodate rapid molecule breakdown leading to high selectivity on pyrolytic liquid containing alkanes, amides, nitryl aliphatic, esters, and long-chain fatty acid [49-51].

 https://doi.org/10.25077/metal.7.2.23-30.2023

3.3. Pyrolytic Products

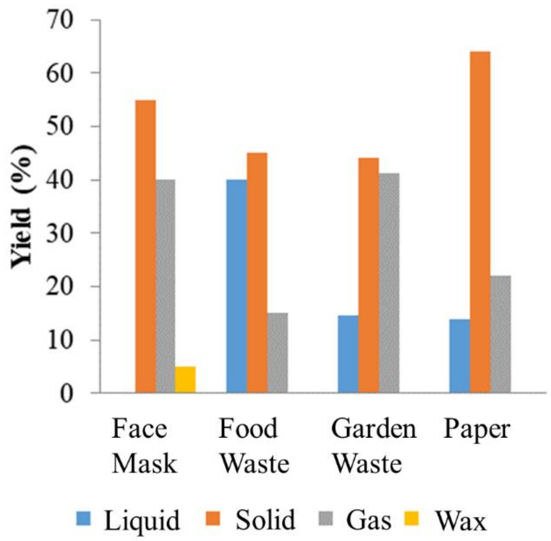

Figure 2. Product Yield of Individual Raw Material Pyrolysis

Pyrolytic liquid mass distribution of the individual raw materials is shown in Figure 2. Food waste pyrolysis produced pyrolytic liquid at the highest distribution since it contained mostly starch and hemicellulose which were degraded at low pyrolysis temperatures [22,52,53]. Face mask pyrolysis produced at around 5% of pyrolytic wax due to the reformation of long-chain hydrocarbon polymer from short-chain hydrocarbon polymer resulted in polypropylene degradation during pyrolysis [3,5,36,54]. Wax formation occurs at around 350-450 °C while pyrolytic liquid formation occurs when the temperatures at around 450-600 °C [55].

In Figure 2, paper pyrolysis produced char with the highest mass distribution due to high lignin content promoting high char selectivity [46]. Char selectivity was also highly promoted with low temperatures leading to low heating rates [16,46].

The highest mass distribution of pyrolytic gas was obtained in pyrolysis of face masks and garden waste. Pyrolytic gas in face mask pyrolysis was resulted from non-condensable short chain hydrocarbon. In garden waste pyrolysis, pyrolytic gas was formed due to high hydrogen content in garden waste as lignocellulosic materials [56-58].

3.4. Co-pyrolysis Products

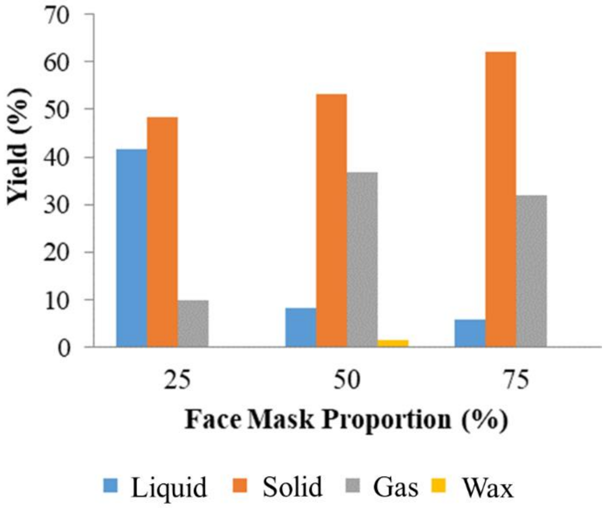

Figure 3. Product Yield of Co-Pyrolysis of Face Mask and Food Waste

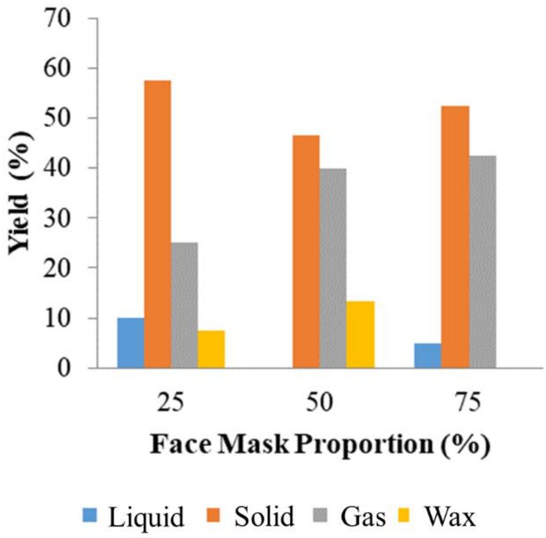

Figure 4. Product Yield of Co-Pyrolysis of Face Mask and Garden Waste

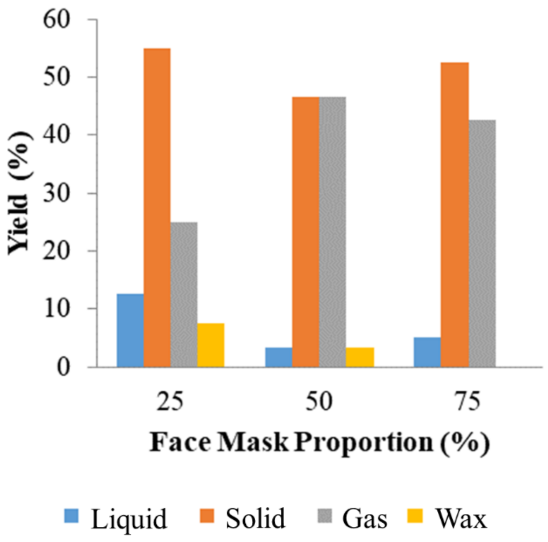

Figure 5. Product Yield of Co-Pyrolysis of Face Mask and Paper

3.4.1. Co-pyrolysis Masks and Food Waste

Pyrolytic product mass distribution of face mask and food waste co-pyrolysis is shown in Figure 3. Three pyrolysis experiments were conducted with varying raw material proportion. The highest pyrolytic oil distribution (41.67%) was obtained from co-pyrolysis of face masks and food waste with ratio of 25:75. Furthermore, high food waste proportion in the raw materials led to high pyrolytic oil distribution. The presence of starch and hemicellulose in food waste enhanced pyrolytic oil yield due to the ease of starch and hemicellulose degradation at around 400 °C [59]. At face mask proportion of 50%, the products contained wax with distribution of 1.67%. The wax originated from the repolymerisation of short-chain organic polymer resulted from the breakdown of polypropylene as the main ingredient of face mask filter [54].

As seen in Figure 3, The highest distribution of pyrolytic char of 62% was obtained in co-pyrolysis of raw materials with 75% of face masks. High face mask proportion promoted large pyrolytic char yield because of high face mask ash composition increasing heat capacity and reducing thermal diffusion of raw materials, leading to slow heating rates [60].

Co-pyrolysis of 50% of face masks produced pyrolytic products with the highest pyrolytic gas distribution. The significant composition of food waste might allow intensive hydrogenation on the food waste via hydrogen donor from face mask and form high concentrations of stable and non-condensable hydrocarbon which increased the distribution of pyrolytic gas. The non-condensable gas is likely to be propane, propylene, ethane, ethylene, methane, hydrogen, and carbon dioxide.

3.4.2. Co-pyrolysis Masks and Garden Waste

In Figure 4, the product distribution results of co-pyrolysis of face masks and garden waste are illustrated. The highest pyrolytic oil yield of 10% was obtained from co-pyrolysis 25% face masks. This yield is significantly lower than that of co-pyrolysis of face masks and food waste since garden waste contained lignin at significantly higher concentration than food waste. Hemicellulose and lignin were the primary source of pyrolytic liquid [39,61]. At face mask proportion of 50%, the pyrolytic wax was formed at a significant distribution of 13.33% due to face mask degradation rate dominance over garden waste [55].

The co-pyrolysis produced pyrolytic char at relatively uniform distribution with face mask of 25% of distribution gave the highest pyrolytic char distribution. High pyrolytic char yield was generally promoted with high ash content [60]. Despite garden waste was dominated with woody biomass with low ash content, high lignin content in garden waste was decomposed at low heating rate and enhanced pyrolytic product selectivity towards pyrolytic char.

Pyrolytic gas distribution was the highest at 42.5% in the co-pyrolysis of 75% of face mask. As explained previously, low lignin content due to low garden waste proportion in the raw materials enhanced heating rate and increased the selectivity towards pyrolytic gas.

 https://doi.org/10.25077/metal.7.2.23-30.2023

3.4.3. Co-pyrolysis Masks and Paper

Pyrolytic product mass distribution of face mask and paper co-pyrolysis is shown in Figure 5. In the co-pyrolysis of 25% of face mask, the highest distribution of pyrolytic oil was obtained. This behaviour was similar to that of co-pyrolysis of face masks and garden waste since papers were also rich in lignin. This similarity also applied to pyrolytic wax formation.

Pyrolytic char also relatively dominated other pyrolytic products with 55%, 46.76%, and 52.5% of pyrolytic char distribution in co-pyrolysis of face masks with proportion of 25%, 50%, and 75%, respectively.

4. CONCLUSIONS

This research focused on co-pyrolysis of hazardous and non-hazardous medical waste, e.g., food waste, garden waste, and papers, to produced pyrolytic products. Co-pyrolysis is considered clean, safe, not complex, and effective to reduce medical waste accumulation during and post-pandemic.

Co-pyrolysis of face masks and either food waste, garden waste, and papers resulted in varying pyrolytic product distribution. The experiments conclude that the co-pyrolysis improves the yield of certain pyrolytic products and diminishes others. With changes of raw material proportion, selectivity towards certain products could be tuned.

DAFTAR PUSTAKA

[1] H. Lukas, C. Xu, Y. Yu, and W. Gao, "Emerging telemedicine tools for remote covid-19 diagnosis, monitoring, and management," *ACS Nano*, vol. 14, no. 12, pp. 16180–16193, 2020, doi: 10.1021/acsnano.0c08494.

[2] S. Trump *et al.*, "Hypertension delays viral clearance and exacerbates airway hyperinflammation in patients with COVID-19," *Nat. Biotechnol.*, vol. 39, no. 6, pp. 705–716, 2021, doi: 10.1038/s41587-020-00796-1.

[3] World Health Organization (WHO), "Rational Use of Personal Protective Equipment for Coronavirus Disease 2019 (COVID-19) and Considerations During Severe Shortages," *Who*, no. March, pp. 1–7, 2020, [Online]. Available: https://apps.who.int/iris/handle/10665/331695

[4] detikNews, "Imbauan Jokowi Pakai Masker Lagi di Outdoor Usai 2 Bulan Pelonggaran," 2022. https://news.detik.com/berita/d-6173264/imbauan-jokowi-pakai-masker-lagi-di-outdoor-usai-2-bulan-pelonggaran

[5] C. Park, H. Choi, K. Y. Andrew Lin, E. E. Kwon, and J. Lee, "COVID-19 mask waste to energy via thermochemical pathway: Effect of Co-Feeding food waste," *Energy*, vol. 230, p. 120876, 2021, doi: 10.1016/j.energy.2021.120876.

[6] J. C. Prata, A. L. P. Silva, T. R. Walker, A. C. Duarte, and T. Rocha-Santos, "COVID-19 Pandemic Repercussions on the Use and Management of Plastics," *Environ. Sci. Technol.*, vol. 54, no. 13, pp. 7760–7765, 2020, doi: 10.1021/acs.est.0c02178.

[7] CNNindonesia, "Limbah Medis Berbahaya Capai 20 Ribu Ton Selama Pandemi Covid," 2021. https://www.cnnindonesia.com/nasional/20210824233340-20-684872/limbah-medis-berbahaya-capai-20-ribu-ton-selama-pandemi-covid

[8] P. Morone, A. Koutinas, N. Gathergood, M. Arshadi, and A. Matharu, "Food waste: Challenges and opportunities for enhancing the emerging bio-economy," *Journal of Cleaner Production*, vol. 221. Elsevier Ltd, pp. 10–16, 2019. doi: 10.1016/j.jclepro.2019.02.258.

[9] V. Kumar, P. Pathak, and N. K. Bhardwaj, "Waste paper: An underutilized but promising source for nanocellulose mining," *Waste Management*, vol. 102. Elsevier Ltd, pp. 281–303, 2020. doi: 10.1016/j.wasman.2019.10.041.

[10] P. Pradhan, A. Arora, and S. M. Mahajani, "Pilot scale evaluation of fuel pellets production from garden waste biomass," *Energy Sustain. Dev.*, vol. 43, pp. 1–14, 2018, doi: 10.1016/j.esd.2017.11.005.

[11] World Health Organization (WHO), "Health-care waste," 2018, [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/health-care-waste

[12] SIPSN, "CAPAIAN KINERJA

PENGELOLAAN SAMPAH," 2021. https://sipsn.menlhk.go.id/sipsn/

[13] V. K. Gaur, P. Sharma, R. Sirohi, M. K. Awasthi, C. G. Dussap, and A. Pandey, "Assessing the impact of industrial waste on environment and mitigation strategies: A comprehensive review," *J. Hazard. Mater.*, vol. 398, p. 123019, 2020, doi: 10.1016/j.jhazmat.2020.123019.

[14] S. Dharmaraj *et al.*, "Pyrolysis: An effective technique for degradation of COVID-19 medical wastes," *Chemosphere*, vol. 275. Elsevier Ltd, p. 130092, 2021. doi: 10.1016/j.chemosphere.2021.130092.

[15] N. Bhattacharjee and A. B. Biswas, "Pyrolysis of Alternanthera philoxeroides (alligator weed): Effect of pyrolysis parameter on product yield and characterization of liquid product and bio char," *J. Energy Inst.*, vol. 91, no. 4, pp. 605–618, 2018, doi: 10.1016/j.joei.2017.02.011.

[16] L. Jiang *et al.*, "Pyrolytic behavior of waste extruded polystyrene and rigid polyurethane by multi kinetics methods and Py-GC/MS," *Fuel*, vol. 222, no. February, pp. 11–20, 2018, doi: 10.1016/j.fuel.2018.02.143.

[17] Y. Ding, O. A. Ezekoye, J. Zhang, C. Wang, and S. Lu, "The effect of chemical reaction kinetic parameters on the bench-scale pyrolysis of lignocellulosic biomass," *Fuel*, vol. 232, no. May, pp. 147–153, 2018, doi: 10.1016/j.fuel.2018.05.140.

[18] D. Zhang, L. Jiang, S. Lu, C. Y. Cao, and H. P. Zhang, "Particle size effects on thermal kinetics and pyrolysis mechanisms of energetic 5-amino-1h-tetrazole," *Fuel*, vol. 217, no. July 2017, pp. 553–560, 2018, doi: 10.1016/j.fuel.2017.12.052.

[19] A. T. Sipra, N. Gao, and H. Sarwar, "Municipal solid waste (MSW) pyrolysis for bio-fuel production: A review of effects of MSW components and catalysts," *Fuel Processing Technology*, vol. 175, no. October 2017. pp. 131–147, 2018. doi: 10.1016/j.fuproc.2018.02.012.

[20] J. Wang *et al.*, "Catalytic fast co-pyrolysis of bamboo sawdust and waste tire using a tandem reactor with cascade bubbling fluidized bed and fixed bed system," *Energy Convers. Manag.*, vol. 180, no. 2, pp. 60–71, 2019, doi: 10.1016/j.enconman.2018.10.056.

[21] H. M. Kadlimatti, B. Raj Mohan, and M. B. Saidutta, "Bio-oil from microwave assisted pyrolysis of food waste-optimization using response surface methodology," *Biomass and Bioenergy*, vol. 123, no. June 2018, pp. 25–33, 2019, doi: 10.1016/j.biombioe.2019.01.014.

[22] A. Gupta and S. Mahajani, "Kinetic studies in pyrolysis of garden waste in the context of downdraft gasification: Experiments and modeling," *Energy*, vol. 208, p. 118427, 2020, doi: 10.1016/j.energy.2020.118427.

[23] S. Ryu *et al.*, "Acid-treated waste red mud as an efficient catalyst for catalytic fast copyrolysis of lignin and polyproylene and ozone-catalytic conversion of toluene," *Environ. Res.*, vol. 191, no. August, p. 110149, 2020, doi: 10.1016/j.envres.2020.110149.

[24] S. Kim *et al.*, "Recent advances in hydrodeoxygenation of biomass-derived oxygenates over heterogeneous catalysts," vol. 21, pp. 3715–3743, 2019, doi: 10.1039/c9gc01210a.

[25] Y. K. Park, J. M. Ha, S. Oh, and J. Lee, "Bio-oil upgrading through hydrogen transfer reactions in supercritical solvents," *Chemical Engineering Journal*, vol. 404, no. August 2020. Elsevier, p. 126527, 2021. doi: 10.1016/j.cej.2020.126527.

[26] E. E. Kwon, T. Lee, Y. S. Ok, D. C. W. Tsang, C. Park, and J. Lee, "Effects of calcium carbonate on pyrolysis of sewage sludge," *Energy*, vol. 153, pp. 726–731, 2018, doi: 10.1016/j.energy.2018.04.100.

[27] J. M. Jung, J. I. Oh, K. Baek, J. Lee, and E. E. Kwon, "Biodiesel production from waste cooking oil using biochar derived from chicken manure as a porous media and catalyst," *Energy Convers. Manag.*, vol. 165, no. March, pp. 628–633, 2018, doi: 10.1016/j.enconman.2018.03.096.

[28] B. B. Uzoejinwa, X. He, S. Wang, A. El-Fatah Abomohra, Y. Hu, and Q. Wang, "Co-pyrolysis of biomass and waste plastics as a thermochemical conversion technology for high-grade biofuel production: Recent progress and future directions elsewhere worldwide," *Energy Conversion and Management*, vol. 163, no. March. Elsevier, pp. 468–492, 2018. doi: 10.1016/j.enconman.2018.02.004.

[29] R. K. Mishra and K. Mohanty, "Co-pyrolysis of waste biomass and waste plastics (polystyrene and waste nitrile gloves) into renewable fuel and value-added chemicals," *Carbon Resour. Convers.*, vol.

3, no. June, pp. 145–155, 2020, doi: 10.1016/j.crcon.2020.11.001.

[30] M. Syamsiro, A. N. Hadiyanto, and Z. Mufrodi, “Rancang Bangun Mesin Pencacah Plastik Sebagai Bahan Baku Mesin Pirolisis Skala Komunal,” *J. Mek. dan Sist. Termal*, vol. 1, no. 2, pp. 43–48, 2016.

[31] A. V Bridgwater, “Review of fast pyrolysis of biomass and product upgrading,” *Biomass and Bioenergy*, vol. 38, pp. 68–94, 2012, doi: 10.1016/j.biombioe.2011.01.048.

[32] M. Hu *et al.*, “Hydrogen-rich gas production by the gasification of wet MSW (municipal solid waste) coupled with carbon dioxide capture,” *Energy*, vol. 90, pp. 857–863, 2015, doi: 10.1016/j.energy.2015.07.122.

[33] W. A. W. Mahari *et al.*, “Microwave co-pyrolysis for simultaneous disposal of environmentally hazardous hospital plastic waste, lignocellulosic, and triglyceride biowaste,” *J. Hazard. Mater.*, vol. 423, p. 127096, 2022, doi: 10.1016/j.jhazmat.2021.127096.

[34] S. Hasan, A. Aladin, T. Syarif, and M. Arman, “Pengaruh Penambahan Gas Nitrogen Terhadap Kualitas Charcoal Yang Diproduksi Secara Pirolisis Dari Limbah Biomassa Serbuk Gergaji Kayu Ulin (Euxideroxylon Zwageri),” *J. Chem. Process Eng.*, vol. 5, pp. 2655–2967, 2020.

[35] S. S. Lam, W. A. Wan Mahari, chin K. Cheng, R. Omar, cheng T. Chong, and H. A. Chase, “Recovery of diesel-like fuel from waste palm oil by pyrolysis using a microwave heated bed of activated carbon,” *Energy*, vol. 115, pp. 791–799, 2016, doi: 10.1016/j.energy.2016.09.076.

[36] S. Jung, S. Lee, X. Dou, and E. E. Kwon, “Valorization of disposable COVID-19 mask through the thermo-chemical process,” *Chem. Eng. J.*, vol. 405, no. August 2020, p. 126658, 2021, doi: 10.1016/j.cej.2020.126658.

[37] S. K. Karmee and C. S. K. Lin, “Valorisation of food waste to biofuel: current trends and technological challenges,” *Theor. Chem. Acc.*, vol. 2, no. 1, pp. 4–7, 2014, doi: 10.1186/s40508-014-0022-1.

[38] A. Gupta, S. K. Thengane, and S. Mahajani, “CO2 gasification of char from lignocellulosic garden waste: Experimental and kinetic study,” *Bioresour. Technol.*, vol. 263, pp. 180–191, 2018, doi: 10.1016/j.biortech.2018.04.097.

[39] A. Zhu, Y. Qin, J. Wu, M. Ye, and Y. Y. Li, “Characterization of biogas production and microbial community in thermophilic anaerobic co-digestion of sewage sludge and paper waste,” *Bioresour. Technol.*, vol. 337, no. May, p. 125371, 2021, doi: 10.1016/j.biortech.2021.125371.

[40] L. Zihare and D. Blumberga, “Market opportunities for cellulose products from combined renewable resources,” *Environ. Clim. Technol.*, vol. 19, no. 1, pp. 33–38, 2017, doi: 10.1515/rtuect-2017-0003.

[41] J. Akhtar and N. saidina A. Amin, “A review on operating parameters for optimum liquid oil yield in biomass pyrolysis,” *Renew. Sustain. Energy Rev.*, vol. 16, no. 7, pp. 5101–5109, 2012, doi: 10.1016/j.rser.2012.05.033.

[42] M. M. Hasan, M. G. Rasul, M. M. K. Khan, N. Ashwath, and M. I. Jahirul, “Energy recovery from municipal solid waste using pyrolysis technology: A review on current status and developments,” *Renewable and Sustainable Energy Reviews*, vol. 145, no. September. Elsevier Ltd, p. 111073, 2021. doi: 10.1016/j.rser.2021.111073.

[43] A. Tomczyk, Z. Sokołowska, and P. Boguta, “Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects,” *Reviews in Environmental Science and Biotechnology*, vol. 19, no. 1. Springer Netherlands, pp. 191–215, 2020. doi: 10.1007/s11157-020-09523-3.

[44] K. Jindo, H. Mizumoto, Y. Sawada, M. A. Sanchez-Monedero, and T. Sonoki, “Physical and chemical characterization of biochars derived from different agricultural residues,” *Biogeosciences*, vol. 11, no. 23, pp. 6613–6621, 2014, doi: 10.5194/bg-11-6613-2014.

[45] J. A. Ippolito *et al.*, “Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review,” *Biochar*, vol. 2, no. 4. Springer Singapore, pp. 421–438, 2020. doi: 10.1007/s42773-020-00067-x.

[46] Y. Li, B. Xing, Y. Ding, X. Han, and S. Wang, “A critical review of the production and advanced utilization of biochar via selective pyrolysis of lignocellulosic biomass,” *Bioresource Technology*, vol. 312, no. May. Elsevier, p. 123614, 2020. doi: 10.1016/j.biortech.2020.123614.

[47] P. Pariyar, K. Kumari, M. K. Jain, and P. S. Jadhao, “Evaluation of change in biochar properties derived from different feedstock

and pyrolysis temperature for environmental and agricultural application," *Sci. Total Environ.*, vol. 713, p. 136433, 2020, doi: 10.1016/j.scitotenv.2019.136433.

[48] E. Rodríguez, R. Palos, A. Gutiérrez, D. Trueba, J. M. Arandes, and J. Bilbao, "Towards waste refinery: Co-feeding HDPE pyrolysis waxes with VGO into the catalytic cracking unit," *Energy Convers. Manag.*, vol. 207, no. October 2019, p. 112554, 2020, doi: 10.1016/j.enconman.2020.112554.

[49] W. N. R. W. Isahak, M. W. M. Hisham, M. A. Yarmo, and T. Y. H. Hin, "A review on bio-oil production from biomass by using pyrolysis method," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 8. Elsevier, pp. 5910–5923, 2012. doi: 10.1016/j.rser.2012.05.039.

[50] B. Biswas, N. Pandey, Y. Bisht, R. Singh, J. Kumar, and T. Bhaskar, "Pyrolysis of agricultural biomass residues: Comparative study of corn cob, wheat straw, rice straw and rice husk," *Bioresour. Technol.*, vol. 237, pp. 57–63, 2017, doi: 10.1016/j.biortech.2017.02.046.

[51] X. Huang *et al.*, "Influences of pyrolysis conditions in the production and chemical composition of the bio-oils from fast pyrolysis of sewage sludge," *J. Anal. Appl. Pyrolysis*, vol. 110, no. 1, pp. 353–362, 2014, doi: 10.1016/j.jaap.2014.10.003.

[52] S. Kim, Y. Lee, K. Y. Andrew Lin, E. Hong, E. E. Kwon, and J. Lee, "The valorization of food waste via pyrolysis," *Journal of Cleaner Production*, vol. 259. Elsevier Ltd, p. 120816, 2020. doi: 10.1016/j.jclepro.2020.120816.

[53] B. Grycová, I. Koutník, and A. Pryszcz, "Pyrolysis process for the treatment of food waste," *Bioresour. Technol.*, vol. 218, pp. 1203–1207, 2016, doi: 10.1016/j.biortech.2016.07.064.

[54] T. A. Aragaw and B. A. Mekonnen, "Current plastics pollution threats due to COVID-19 and its possible mitigation techniques: a waste-to-energy conversion via Pyrolysis," *Environ. Syst. Res.*, vol. 10, no. 1, 2021, doi: 10.1186/s40068-020-00217-x.

[55] M. S. Qureshi *et al.*, "Pyrolysis of plastic waste: Opportunities and challenges," *J. Anal. Appl. Pyrolysis*, vol. 152, no. October 2019, 2020, doi: 10.1016/j.jaap.2020.104804.

[56] Z. Luo, X. Zhu, J. Deng, K. Gong, and X. Zhu, "High-value utilization of mask and heavy fraction of bio-oil: From hazardous waste to biochar, bio-oil, and graphene films," *J. Hazard. Mater.*, vol. 420, no. May, p. 126570, 2021, doi: 10.1016/j.jhazmat.2021.126570.

[57] B. Grycova, A. Pryszcz, P. Lestinsky, and K. Chamradova, "Influence of potassium hydroxide and method of carbonization treatment in garden and corn waste microwave pyrolysis," *Biomass and Bioenergy*, vol. 118, no. July, pp. 40–45, 2018, doi: 10.1016/j.biombioe.2018.07.022.

[58] H. Siddiqui, S. K. Thengane, S. Sharma, and S. M. Mahajani, "Revamping downdraft gasifier to minimize clinker formation for high-ash garden waste as feedstock," *Bioresour. Technol.*, vol. 266, no. June, pp. 220–231, 2018, doi: 10.1016/j.biortech.2018.06.086.

[59] D. Zhong *et al.*, "Characteristics and evolution of heavy components in bio-oil from the pyrolysis of cellulose , hemicellulose and lignin," *Renew. Sustain. Energy Rev.*, vol. 157, no. December 2021, p. 111989, 2022, doi: 10.1016/j.rser.2021.111989.

[60] K. Cen, J. Zhang, Z. Ma, D. Chen, J. Zhou, and H. Ma, "Investigation of the relevance between biomass pyrolysis polygeneration and washing pretreatment under different severities: Water, dilute acid solution and aqueous phase bio-oil," *Bioresour. Technol.*, vol. 278, no. November 2018, pp. 26–33, 2019, doi: 10.1016/j.biortech.2019.01.048.

NOMECLATURE

L	pyrolytic liquid mass percentage (%)
S	pyrolytic solid mass percentage (%)
G	pyrolytic gas mass percentage (%)
W	pyrolytic wax mass percentage (%)
m	sample mass before pyrolysis (gram)
m_2	pyrolytic liquid mass (gram)
m_3	pyrolytic solid mass (gram)
m_4	pyrolytic wax mass (gram)

 https://doi.org/10.25077/metal.7.2.23-30.2023