

## BIO-CHAR AND BIO-OIL PRODUCTION FROM PYROLYSIS OF PALM KERNEL SHELL AND POLYETHYLENE

Nur Rahimah IBRAHIM<sup>1</sup>, Razi AHMAD<sup>1,2\*</sup>, Wan Amiza Amneera WAN AHMAD<sup>1,2</sup>, Vijean VIKNESWARAN<sup>3</sup>, Rangunathan SANTIAGOO<sup>1,4</sup>, Syakirah Afiza MOHAMMED<sup>1,2</sup>, Amrie Fadruz KHALID<sup>1</sup>, Asnida Yanti ANI<sup>5</sup>

<sup>1</sup>Faculty of Civil Engineering & Technology, Universiti Malaysia Perlis, 02600 Arau, Perlis, Malaysia

<sup>2</sup>Water Research and Environmental Sustainability Growth (WAREG), Center of Excellence (COE), Universiti Malaysia Perlis (UniMAP), Perlis, Malaysia

<sup>3</sup>Faculty of Electronic Engineering Technology, Universiti Malaysia Perlis, Pauh Putra Campus, Perlis, Malaysia

<sup>4</sup>Sustainable Environment Research Group (SERG), Center of Excellence Geopolymer and Green Technology, Universiti Malaysia Perlis, Perlis, Malaysia

<sup>5</sup>Faculty of Applied Science, University Teknologi MARA, Perlis Branch, Arau Campus, Arau, Perlis, Malaysia

### Abstract

*In recent years, palm kernel shell (PKS) has become a viable feedstock for making biofuels and value-added commodities using a variety of thermal conversion routes. Therefore, significant conservation is required for PKS as a resource for fuel production in biofuel facilities. Thus, this research was intended to elucidate the effects on PKS as a solid fuel through torrefaction and the production of bio-char and bio-oil by single and co-pyrolysis of PKS and polyethylene (PE). The PKS was treated through torrefaction at different temperatures and holding times. The optimum parameters for torrefaction were a temperature of 250 °C and a holding time of 60 min. Then the PKS and PE were pyrolyzed in a fixed-bed reactor at different temperatures and ratios. The product yield was analysed for single and co-pyrolysis of PKS and PE for pyrolysis. The properties of the product composition for single and co-pyrolysis of the PKS and PE were determined by proximate analysis, Fourier transform infrared (FTIR) analysis, and gas chromatography-mass spectrometry (GC-MS). The optimum parameter obtained for bio-char and bio-oil production from co-pyrolysis of PKS and PE was at temperature of 500 °C at a ratio of 1:2 (PKS: PE). The ester and phenol compounds were increased around 19.02 to 23.18% and 32.51 to 34.80 %, respectively, while amide and amine decreased around 4.94 to 18.87% and 0.63 to 32.39 %, respectively, compared to the single pyrolysis of PKS. Therefore, the PKS and PE co-pyrolysis significantly increased the amount of phenol and ester compounds while slightly reducing the amount of amide and amine compounds in the bio-oil product. As a conclusion, biomass conservation enables the manufacturing of value-added chemicals.*

**Keywords:** Torrefaction; Biomass; Thermal Conversion; Pyrolysis; Bio-char; Bio-oil

### Introduction

Nowadays, plastic materials are used for domestic purposes. Hence, plastics' lightness, dexterity, versatility, and low manufacturing cost have made them a highly desirable material for utility in various sectors. Polyethylene (PE) is one of the plastics that contributes approximately 33% of global plastic waste exports, and 30% is from demand from European plastic conversion in 2017. Nine developing countries with fast-growing market economies are major importers and exporters of the global PE waste trade [1]. Five of the nine major importers and exporters of PE

\* Corresponding author: razi@unimap.edu.my

waste are Brazil, Malaysia, China, Turkey, and Taiwan [2]. PE has good physicochemical properties and is easy to melt and mould for recycling. The various types of PE include High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE), and Linear Low-Density Polyethylene (LLDPE) [3].

Biomass is considered a significant future alternative energy source. Biomass feedstocks include wood, industrial and agricultural residues, and by-products such as sawdust, wood chip, bagasse, rice husk, and dedicated energy crops that are typically used as biomass fuels [4]. Natural sources for biomass come in a vast range, and annual worldwide biomass production was predicted to be around 100 billion tonnes [5]. On thermochemical treatment, the high carbon content of biomass turns it into high-energy bio-char. Among the few well-established thermochemical processes for treating biomass and biogenic waste to provide high-energy char in addition to oil and gaseous yields [6].

The most widely used method of producing bio-char from biomasses is pyrolysis, which involves a thermochemical decomposition process under an oxygen-depleted atmosphere at high temperatures [7]. Pyrolysis is a potential technology for converting biomass into bio-char, bio-oil, and gas at temperatures ranging from 400 to 650°C under nitrogen conditions. Pyrolysis is a thermal conversion mechanism that occurs in four stages: moisture evolution (220°C), hemicellulose breakdown (220–350°C), cellulose decomposition (315–400°C), and lignin decomposition (> 400°C) [8].

Therefore, in this research, single and co-conversion were studied on biomass and plastic waste. Thermochemical conversion, such as pyrolysis, was utilised to overcome the problem. The outcomes between single and co-conversion of the biomass and plastic waste were investigated on the characteristics of PKS and PE and evaluated on the pyrolysis product quality of bio-char (solid) and bio-oil (liquid).

## Experimental part

### *Materials*

PKS and PE were the biomass and plastic, respectively, employed in the single and co-pyrolysis processes. The PKS was collected from United Oil Palm Mill Sdn Bhd, Nibong Tebal, Pulau Pinang, and the PE was obtained from the UiTM Arau, Perlis Laboratory. PKS is the shell material left after the nut has been removed after crushing in the palm oil mill. It was dried in the oven at a temperature of 110°C for 1.5 hours to remove the moisture content. Using a crusher, the PKS was reduced to a small size. The PKS was sieved using a sieve shaker to separate the particle sizes with diameters between 300–600µm.

### *Single and Co-Pyrolysis Process*

A fixed bed reactor was used for the biomass pyrolysis experiments. The reactor tube was filled with  $10 \pm 0.5$ g PKS. A heating rate of 80°C/min and a constant flow rate of N<sub>2</sub> at 0.5L/min were used in the pyrolysis experiment to achieve an inert atmosphere. The pyrolysis yield from the various parameters of the pyrolysis process was investigated by identifying the effects of temperature (400°C and 500°C) and the ratio of PKS and PE (1:0, 0:1, 1:1, 1:2, and 2:1). The char and bio-oil products were weighed to calculate the percentage of the yield. The gas produced was calculated by dividing the differences. The bio-oil was analysed using Fourier-transform infrared spectroscopy (FTIR) and Gas chromatography–mass spectrometry (GC-MS).

## Results and discussion

### *Proximate Analysis of Treated PKS*

Table 1 displays the result of the proximate analysis for treated PKS. Generally, it can be seen that the moisture content and volatile matter of treated PKS decreased when the temperature of torrefaction increased. This was due to the increased heat demand for moisture evaporation

and occurring decomposition reaction [9]. Meanwhile, ash content and fixed carbon increase for treated PKS due to the release of some of the mineral matter (alkali metal, Cl, and sulphur) during the torrefaction process [9, 10]. The increased amount of fixed carbon was due mainly to the increases in the devolatilization rate as the torrefaction temperature increased, where hemicellulose and lignin breakdown became more relevant as the temperature increased [12].

The amount of moisture content and fixed carbon indicated that treated PKS is a suitable fuel feedstock to conduct thermal conversion. After torrefaction, the moisture content of treated PKS significantly decreased while fixed carbon increased with increasing temperature torrefaction. The treated PKS was 7.92 to 1.90% and 4.56 to 14.52% when the temperature increased to 250°C at a holding time of 60min.

**Table 1.** Proximate analysis of treated PKS

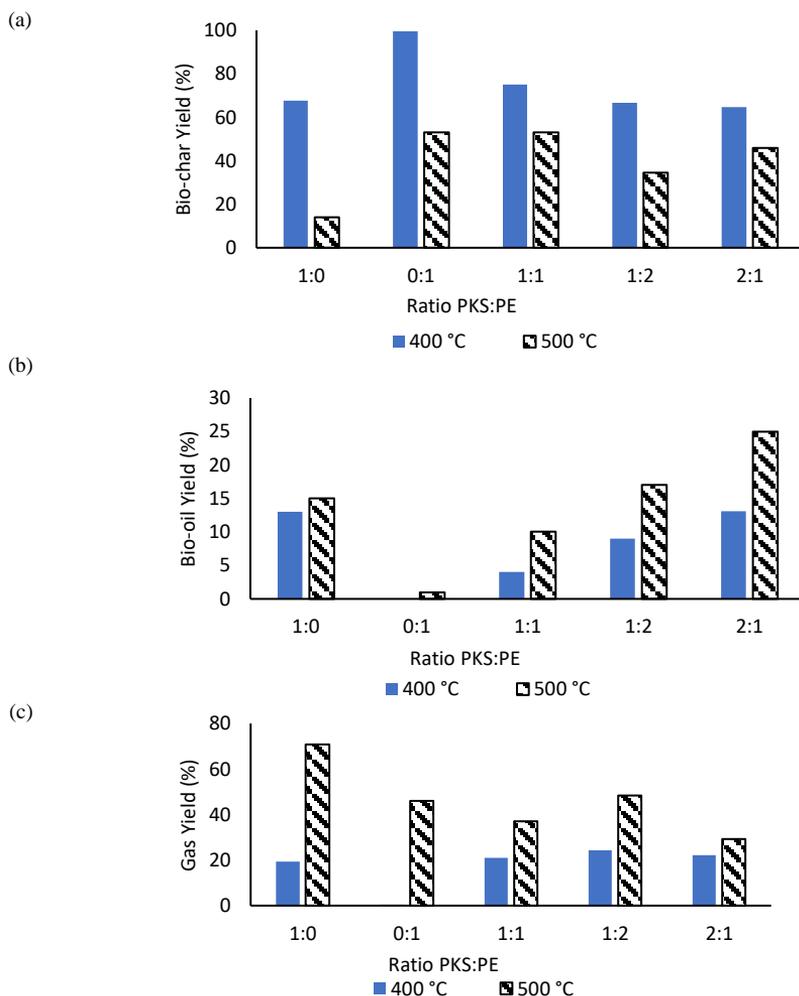
Sample	Proximate Analysis (wt %)			
	Moisture Content	Volatile Matter	Ash Content	Fixed Carbon
Raw PKS	7.92	78.42	9.10	4.56
PKS 200 °C (30-minutes)	2.68	77.75	7.77	11.80
PKS 200 °C (60-minutes)	2.66	74.73	8.99	13.62
PKS 200 °C (90-minutes)	1.81	81.45	8.60	8.14
PKS 250 °C (30-minutes)	2.49	76.39	10.50	10.62
PKS 250 °C (60-minutes)	1.90	73.18	10.41	14.52
PKS 250 °C (90-minutes)	2.43	76.78	9.44	12.34
PKS 300 °C (30-minutes)	1.00	73.01	10.76	15.23
PKS 300 °C (60-minutes)	0.86	64.96	11.76	22.42
PKS 300 °C (90-minutes)	0.33	67.71	13.81	18.15

***Effect of Temperature and Ratio of PKS and PE on Pyrolysis Product Yield***

The bio-char yield from pyrolysis of PKS and PE at temperatures ranging from 400°C to 500°C with a holding time of 60min and various ratios of PKS to PE is demonstrated in figure 1a. The optimum parameter obtained for bio-char from co-pyrolysis of PKS and PE was 400°C at a ratio of 1:1. This was due to the fact that the production of bio-char increased by 7.3% compared to the single pyrolysis of PKS. The result shows that the trend is clearly decreasing when the temperature rises. At 400°C, the char yield was high, more than 64% for all ratios of PKS to PE, while at 500°C, 14 to 53% were produced compared to single pyrolysis PKS. This was due to the bridge bond between fundamental structural units of carbon being broken and gaseous hydrocarbons escaping from the system after aliphatic side chains are broken, releasing free radicals and active hydrogen at the same time [13]. Bond fission becomes easier as the temperature increases. *J.a. Oyebanji et al.* [14] reported that the kinetics of samples to volatiles have been improved by temperature changes, and several researchers agreed that as temperature increased, the bio-char yield decreased.

The bio-oil yield from pyrolysis of PKS and PE at temperatures ranging from 400 to 500°C with a holding time of 60min and various ratios of PKS to PE was demonstrated in figure 1b. The optimum parameter for the bio-oil was at 500°C for a ratio of 2:1. As can be seen, the ratio of PKS:PE of 2:1 shows the highest bio-oil yield of 25%. Enrichment of the bio-oil was due to the presence of the major hydrogen compounds in the PE [15]. The polyolefin polymers such as PE have a great hydrogen source during co-pyrolysis, which can contribute to the significant increase in bio-oil during co-pyrolysis of biomass and plastic waste [15]. The increase in bio-oil when the temperature increased was due to the kinetics of the sample to volatiles being enhanced when the temperature increased [14].

The gas yield from pyrolysis of PKS and PE at temperatures of 400 to 500°C in a holding time of 60min with the various ratios of PKS to PE is shown in Figure 1c.



**Fig. 1** Effect of temperature and ratios of PKS and PE on: (a) bio-char yield, (b) bio-oil yield and (c) gas yield

The optimum parameter for the gas yield was 500°C at a ratio of 1:2. This was due to the chemical bond between fundamental structural elements being broken and bond fission becoming easier as the temperature increased [14]. Besides, the presence of the PE increased the production of gas yield, which contains high amounts of hydrogen and carbon, and it contributed to the increase in the value of gas yield [16]. The highest gas yield is at 500°C for 60min for all ratios compared to 400°C for 60min. The generation of gases is mostly related to biomass structures rather than elemental content [17]. When the pyrolysis temperature became too high, secondary cracking of the pyrolysis vapour occurred, causing the gas yield to increase as the bio-oil eventually decreased [18].

**Characterization of the Pyrolysis Product (Bio-char)**

Table 2 shows the proximate analysis of pyrolysis PKS and PE under different temperatures and ratios. Generally, the amount of ash content for co-pyrolysis of PKS and PE slightly increased from 0.5% to 1.5% when the temperature increased from 400°C to 500°C compared with the pyrolysis of individual PKS, which significantly increased by about 57%.

**Table 2.** Proximate analysis of pyrolysis of PKS and PE under different temperature and ratio

Sample	Ratio	Proximate analysis (wt%)		
		Volatile matter	Ash content	Fixed carbon
PKS (400 °C)	1:0	71.42	16.74	10.18
PKS (500 °C)	1:0	14.16	73.12	11.10
PE (400 °C)	0:1	97.50	0.70	0.43
PE (500 °C)	0:1	97.96	0.64	0.07
PKS and PE (400 °C)	1:1	87.27	6.36	5.28
PKS and PE (500 °C)	1:1	81.93	7.92	8.85
PKS and PE (400 °C)	1:2	87.88	4.72	6.26
PKS and PE (500 °C)	1:2	82.28	6.38	9.50
PKS and PE (400 °C)	2:1	83.44	8.33	6.38
PKS and PE (500 °C)	2:1	81.86	8.85	7.37

This is due to the fact that biomass such as PKS contains a high amount of alkali metal [10]. The ash content decreased when the PE ratio increased. The presence of the PE had reduced the amount of ash content, which dropped to 66% compared to the single pyrolysis of PKS, which had the highest amount of ash content. The amount of volatile matter for co-pyrolysis reduced by around 1% to 5% at 400°C to 500°C compared to single pyrolysis of PKS, which reduced by about 57%. This was due to the decomposition reaction occurring at a higher temperature. Therefore, it caused the reduction of volatile matter and increased the fixed carbon [9]. Moreover, the volatile matter increased when the ratio of PE increased due to the high volatile matter of PE [19]. *B.B. Uzoejinwa et al.* [16] reported that the PE was a good hydrocarbon source with high hydrogen and carbon content, which contributed to the increased volatile matter content. Hence, mixing the PE with PKS increased the amount of volatile matter compared to the single pyrolysis of PKS. The amount of fixed carbon for single pyrolysis samples PKS and PE decreased when the temperature started increasing from 400°C to 500°C at 60min. Meanwhile, for co-pyrolysis for PKS and PE with ratios of 1:1, 1:2, and 2:1, the amount of fixed carbon increased when the temperature increased from 400 to 500°C at a holding time of 60min. In the single pyrolysis of PKS, the amount of fixed carbon increases by around 1%. This was due to the decrease in the amount of volatile matter as the temperature increased. *T.Y. Ahmad et al.* [9] stated that the decomposition reaction occurred at a high temperature, which caused the reduction of volatile matter and increased the fixed carbon. Meanwhile, the single pyrolysis for PE decreased by around 1% when the temperature increased. This was the reason that the PE was a good hydrocarbon source that contained high levels of hydrogen and carbon and contributed to the increased value of volatile matter [16].

Therefore, the optimum parameter obtained for bio-char production from co-pyrolysis of PKS and PE is 500°C at a ratio of 1:2. This was because the ash content for co-pyrolysis of PKS and PE significantly decreased by around 66.74% compared to single pyrolysis of PKS. Meanwhile, the volatile matter of co-pyrolysis PKS and PE significantly increased by around 68.12% compared to single pyrolysis PKS. This was due to the increased temperature and the presence of PE, which contains a good source of hydrocarbons. Next, the amount of fixed carbon for co-pyrolysis of PKS and PE at 500°C for a ratio of 1:2 slightly decreased by around 1.6% compared to single pyrolysis of PKS. This was due to the increased temperature where the decomposition occurs. Therefore, the co-pyrolysis of the PKS and PE slightly reduced the fixed carbon while enhancing the volatile matter and reducing the ash content.

#### **Characterization of the Pyrolysis Product (Bio-oil)**

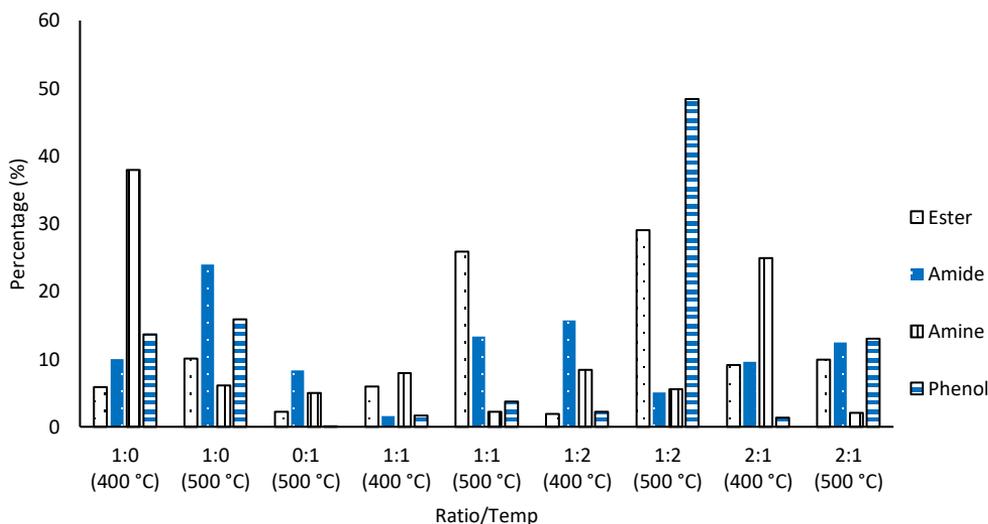
Table 3 demonstrates the functional group compositions of bio-oil obtained from single and co-pyrolysis of PKS and PE. The presence of phenol and alcohol was found at the O=H stretching peak at 3365 to 3386cm<sup>-1</sup> for ratios 1:0 (at both temperatures), 1:2 (at both temperatures), and 2:1 (at 400°C). Meanwhile, there were also showed C – H stretching vibrations at 2916 and 2848cm<sup>-1</sup> in the single pyrolysis of PE, which is 0:1 (500°C) and in the co-pyrolysis of PKS and PE, which is 1:1 (400°C), 1:1 (500°C), and 2:1 (500°C). This showed the presence of

alkanes and alkenes. Furthermore, the presence of ketones, carboxylic acid, and aldehydes was found at the C=O stretching peak at 1642 and 1708cm<sup>-1</sup> for all ratios and temperatures of bio-oil production from single and co-pyrolysis PKS and PE. Besides that, there were illustrated C – O stretching vibrations at 1230 and 1320cm<sup>-1</sup> for all ratios and temperatures of bio-oil which showed the presence of alkanes, alcohols, phenols, ethers, and lipids.

**Table 3.** Functional group of bio-oil

Wavenumber (cm <sup>-1</sup> )	Bond	Functional group	References
3700 – 3000	O – H stretching vibration	Phenolic, alcoholic and carboxylic	[20]
3000–2700	C – H stretching vibration	CH <sub>4</sub>	[21]
1900 - 1650	C=O	Aldehydes, ketones, acids	[22]
1475 – 1000	C – O, C – C and carbon chain skeleton stretching vibration	Alkanes, alcohols, ethers, and lipids	[23], [24]
1300 – 1200	C – O stretching vibration	Phenols	[25]
1275 – 1060	C – O stretching vibration	Ethers	[25]
1200 – 1000	C – O stretching vibration	Alcohols	[25]

Figure 2 shows the chemical compound in the bio-oil product of single and co-pyrolysis of PKS and PE. It was found that several groups of chemical compounds, including ester, amide, amine, and phenol. The optimum parameter obtained for bio-oil production from co-pyrolysis of PKS and PE is at temperature 500°C for a ratio of 1:2. At the optimum parameter, the amount of the phenol compound increasing around 32.51 - 34.80% compared with single pyrolysis of PKS.



**Fig. 2.** The chemical compound in bio-oil product of single and co-pyrolysis PKS and PE under different temperature and ratio

**Conclusions**

Pretreatment of PKS was recommended before undergoing thermal conversion to increase the quality of the raw PKS, which was optimised at a torrefaction temperature of 250°C and a holding time of 60 min. The maximum yield of bio-char and bio-oil increased by around 7.3% and 10%, respectively, at pyrolysis temperatures of 400°C for a ratio of 1:1 and 500°C for a ratio of 2:1. The properties of the bio-char and bio-oil for single and co-pyrolysis of the PKS and PE were important to produce high quality of solid fuel and bio-oil. The result showed the

optimum parameter obtained for bio-char and bio-oil was at a temperature of 500°C for a ratio of 1:2, where it enhanced the amount of volatile matter, reduced a large amount of ash content, and significantly increased the amount of phenol. Therefore, the results of this work can enhance the entire biofuel production system by conserving biomass, enabling it to be utilised more profitably throughout the year in biofuel facilities.

### **Acknowledgments**

The authors would like to acknowledge the support from the Fundamental Research Grant Scheme (FRGS) under a grant number of FRGS/1/2021/STG04/UNIMAP/02/1 from the Ministry of Higher Education Malaysia. The authors would like to express their gratitude to the Environmental Engineering Laboratory, Faculty of Civil Engineering & Technology, UniMAP for providing the facilities on this research.

### **References**

- [1] M. Olteanu, A. Baraitaru, A. M. Panait, D. Dumitru, M. Boboc, G. Deák, *Advanced SiO<sub>2</sub> Composite Materials for Heavy Metal Removal from Wastewater*, **Water Air Soil Pollution**, **230**, 2019, Article Number: 179, DOI: 10.1007/s11270-019-4225-7.
- [2] G. Deak, F.D. Dumitru, M.A. Moncea, A.M. Panait, A.G. Baraitaru, M.V. Olteanu, M.G. Boboc, S. Stanciu, *Synthesis of ZnO nanoparticles for water treatment applications*, **International Journal of Conservation Science**, **10**, 2019, pp. 343–350.
- [3] W. Xu, W. Q. Chen, D. Jiang, C. Zhang, Z. Ma, Y. Ren, L. Shi, *Evolution of the global polyethylene waste trade system*, **Ecosystem Health Sustainability**, **6**, 2020, pp. 1-16
- [4] V.M. Radu, A.A. Ivanov, P. Ionescu, G. Deak, E. Diacu, *Overall assessment of water quality on lower danube river using multi-parametric quality index*, **Revistade Chimie**, **67**, 2016, pp. 391–395.
- [5] H.C. Ong, K.L. Yu, W.H. Chen, M.K. Pillejera, X. Bi, K.Q. Tran, A. Petrissans, M. Petrissans, *Variation of lignocellulosic biomass structure from torrefaction: A critical review*, **Renewable and Sustainable Energy Reviews**, **152**, 2021, Article Number: 111698. DOI: 10.1016/j.rser.2021.111698.
- [6] M. Tripathi, J.N. Sahu, P. Ganesan, *Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review*, **Renewable and Sustainable Energy Revision**, **55**, 2016, pp. 467–481.
- [7] R. Chatterjee, B. Sajjadi, W.Y.Chen, D.L. Mattern, N. Hammer, V. Raman, A. Dorris, *Effect of Pyrolysis Temperature on PhysicoChemical Properties and Acoustic-Based Amination of Biochar for Efficient CO<sub>2</sub> Adsorption*, **Frontiers in Energy Research**, **8**, 2020, pp. 1–18.
- [8] N.N. Kasim, K. Ismail, A.R. Mohamed, M.A.M. Ishak, R. Ahmad, W.I.N.W. Ismail, *Characteristic, thermochemical behaviors and kinetic of demineralized and torrefied empty fruit bunches (EFB)*, **Advances in Science Technology Engineering Systems Journal**, **3**, 2018, pp. 365–373.
- [9] T.Y. Ahmad, T. Hirajima, S. Kumagai, K. Sasaki, *Production of solid biofuel from agricultural wastes of the palm oil industry by hydrothermal treatment*, **Waste and Biomass Valorization**, **1**, 2010, pp. 395–405.
- [10] Q.V. Bach and O. Skreiberg, *Upgrading biomass fuels via wet torrefaction: A review and comparison with dry torrefaction*, **Renewable and Sustainable Energy Revision**, **54**, 2019, pp. 665–677.
- [11] A.M. Anghel, E. Diacu, M. Ilie, A. Petrescu, G. Ghita, F. Marinescu, G. Deak, *Statistical analysis of heavy metals concentration in water and sediments in the lower part of the Danube River-Romanian section*, **Revistade Chimie**, **67**, 2016, pp. 2151–2155.

- [12] H. Mohd Faizal, H. S. Shamsuddin, M. H. M. Harif, M. F. Muhammad Arif Hanaffi, M. R. Abdul Rahman, M. M. Rahman, Z. A. Latiff, *Torrefaction of densified mesocarp fibre and palm kernel shell*, **Renewable Energy**, **122**, 2018, pp. 419–428.
- [13] C. Qian, M. Zhou, J. Wei, P. Ye, X. Yang, *Pyrolysis and co-pyrolysis of lignite and plastic*, **International Journal of Mining Science Technology**, **24**, 2014, pp. 137–141.
- [14] J.A. Oyebanji, P.O. Okekunle, O.A. Lasode, S.O. Oyedepo, *Chemical composition of bio-oils produced by fast pyrolysis of two energy biomass*, **Biofuels**, **9**, 2018, pp. 479–487.
- [15] A. Dewangan, D. Pradhan, R.K. Singh, *Co-pyrolysis of sugarcane bagasse and low-density polyethylene: Influence of plastic on pyrolysis product yield*, **Fuel**, **185**, 2016, pp. 508–516.
- [16] B.B. Uzoejinwa, X. He, S. Wang, A. El-Fatah Abomohra, Y. Hu, 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**, **163**, 2018, pp. 468–492.
- [17] X. Hu, H. Guo, M. Gholizadeh, B. Sattari, Q. Liu, *Pyrolysis of different wood species: Impacts of C/H ratio in feedstock on distribution of pyrolysis products*, **Biomass and Bioenergy**, **120**, 2019, pp. 28–39.
- [18] S. Suttibak, *Influence of reaction temperature on yields of bio-oil from fast pyrolysis of sugarcane residues*, **Engineering and Applied Science Research**, **44**, 2017, pp. 142–147.
- [19] R.A. Moghadam, S. Yusup, Y. Uemura, B.L.F. Chin, H.L. Lam, A. Al Shoaibi, *Syngas production from palm kernel shell and polyethylene waste blend in fluidized bed catalytic steam co-gasification process*, **Energy**, **75**, 2014, pp. 40–44.
- [20] M. Asadieraghi, W.M.A. Wan Daud, *Characterization of lignocellulosic biomass thermal degradation and physiochemical structure: Effects of demineralization by diverse acid solutions*, **Energy and Conversion Management**, **82**, 2014, pp. 71–82.
- [21] Y. Ding, O.A. Ezekoye, S. Lu, C. Wang, *Thermal degradation of beech wood with thermogravimetry/Fourier transform infrared analysis*, **Energy and Conversion Management**, **120**, 2016, pp. 370–377.
- [22] F. Li, S.C. Tang, *Targeting metastatic breast cancer with ANG1005, a novel peptide-paclitaxel conjugate that crosses the blood-brain-barrier (BBB)*, **Genes & Diseases**, **4**, 2017, pp. 1–3.
- [23] Z. Ma, D. Chen, J. Gu, B. Bao, Q. Zhang, *Determination of pyrolysis characteristics and kinetics of palm kernel shell using TGA-FTIR and model-free integral methods*, **Energy and Conversion Management**, **89**, 2015, pp. 251–259.
- [24] Z. Ma, C. Trevisanut, C. Neagoe, D. C. Boffito, S. M. Jazayeri, C. Jagpal, G. S. Patience, *A micro-refinery to reduce associated natural gas flaring*, **Sustainable Cities Social**, **27**, 2016, pp. 116–121.
- [25] Z. Ma, J. Wang, Y. Yang, Y. Zhang, C. Zhao, Y. Yu, S. Wang, *Comparison of the thermal degradation behaviors and kinetics of palm oil waste under nitrogen and air atmosphere in TGA-FTIR with a complementary use of model-free and model-fitting approaches*, **Journal of Analytical and Applied Pyrolysis**, **134**, 2018, pp. 12–24.

---

Received: October 12, 2022

Accepted: May 24, 2023