Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Bio-oil Production from Rice Husk Pyrolysis using NiO/Rice Husk Ash Catalyst

Arif Hidayat

arif.hidayat@uii.ac.id

Universitas Islam Indonesia, Universitas Islam Indonesia

Bachrun Sutrisno

Universitas Islam Indonesia, Universitas Islam Indonesia

Is Fatimah

Universitas Islam Indonesia

Research Article

Keywords: bio-oil, catalyst, nickel, pyrolysis, rice husk ash

Posted Date: November 23rd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9118135/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Bio-oil Production from Rice Husk Pyrolysis using NiO/Rice Husk Ash Catalyst

Arif Hidayat[a,*], Bachrun Sutrisno[a], Is Fatimah[b]
[a]*Department of Chemical Engineering, Universitas Islam Indonesia, Universitas Islam Indonesia, Indonesia*
[b]*Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Islam Indonesia, Indonesia*
**Coressponding author: arif.hidayat@uii.ac.id*

Abstract
The rice husk pyrolysis was studied using the NiO/RHA catalysts. The NiO/RHA catalysts were prepared by impregnating the nickel oxide as active components on RHA. The NiO/RHA catalyst characteristics were analyzed by nitrogen adsorption-desorption, X-Ray Diffraction (XRD), and Energy Dispersive X-Ray (EDX). The NiO/RHA catalyst was examined for the rice husk pyrolysis in the batch experiment. Several process variables i.e., temperature (400 to 600 °C), catalyst addition, nitrogen gas flow rate (100 to 300 cm^3/min), and heating rate (10 to 30°C/min) were investigated. The Gas Chromatography Mass Spectrometer (GC-MS) and FTIR analysis were carried out to determine the chemical compositions of liquid products. The experiment concluded that using the NiO/RHA catalyst increased in the liquid yield, while decreasing the char yield. It also has been found that the addition of a catalyst, flow rate of nitrogen gas, and rate of heating influenced the liquid yield. The liquid yield reached at maximum when the operation conditions were the temperature of 600°C, nitrogen gas flow rate of 300 cm^3/min, and heating rate of 30 °C.min^{-1}.
Keywords: bio-oil, catalyst, nickel, pyrolysis, rice husk ash

Introduction
The increasing consumption of fossil fuel has been encouraged by the global population growth and industrialization. It will lead to a problem on fulfillment of fuel due to the limitation discovering of fossil fuel resources [1]. Meanwhile, the conscious of environmental protection promotes the application of renewable alternative energy in many sectors. Nowadays, almost 85% of energy production is sourced from fossil fuels. Many industries have searched the alternative energy from renewable resources to reduce the dependency from fossil fuels as well as to substitute them with renewable energy. Biomass is one type of renewable source that can produce energy for replacing fossil fuels [2]. Biomass could generate the energy via thermochemical process [3]. Pyrolysis is a thermochemical process that produces fuel from biomass by heating without the presence of oxygen [4]. The products of pyrolysis process are gases, liquids, and char. The gaseous product is known as synthetic gas, which contains H_2, CO, and CO_2 [5]. The liquids product is known as bio-oil that has a dark brown color and is composed of several organic compounds.
In Indonesia, there is a huge quantity of biomass which potentially can be used as feedstock to generate biofuel through the pyrolysis process. Many agricultural residue, forest industry, plantation are the resource of biomass. The lignocellulosic materials (cellulose, hemicellulose and lignin) on biomass will degrade and form organic compounds during pyrolysis process at high temperature [6]. Pyrolysis can use various biomasses such as rice husk [7, 8], corn cob (Biswas et al., 2017), palm oil empty fuit bunch [9], rice straw (Biswas et al., 2017; Jin et al., 2019), sugarcane bagasse [10], coconut shell [11], sawdust [12], palm kernel shell (Terry et al., 2021), waste tea (Zhou et al., 2024), wheat straw [13, 14], coffee grounds (Kim et al., 2019), plantation residue [15], and aquatic biomass [16-19]. The forming of organic compounds from

lignocellulosic materials on biomass during pyrolysis was composed into three steps: (i) hemicellulose degradation at the temperature of 180-240 °C, (ii) cellulose decomposition at the temperature of 230-360 °C, and (iii) the lignin destruction at the temperature of 280-500 °C [20].

Biomass pyrolysis has been investigated by some researchers, however, one of the problems related to the pyrolysis product is the bio-oil quality. Bio-oil needs to upgrade for enhancing the properties, i.e. heating value, density, viscosity, acidity, and corrosiveness [21]. The upgraded bio-oil will have equal in quality and stability compared with the diesel from fossil fuels. The distribution of product and chemical composition was influenced by several parameters, such as temperature, time, rate of heating, catalyst, Nitrogen gas flow rate, and particle size. The addition of a catalyst influence the distribution and chemical compositions of pyrolysis product. The cracking of heavy organic fractions to form the light organic portions can be done by the addition of catalyst during pyrolysis. The bio-oil stability and heating value could be increased by reducing the oxygenated compounds via hydrodeoxygenation reactions using catalyst [22].

In the last decades, many reported studies have extensively investigated several catalysts for biomass catalytic pyrolysis, including synthetic zeolites [23-25], metal oxide [26-28], natural zeolite [29-31], clay [32], and dolomite [33]. Rice husk can be synthesized as catalyst support by conducting some preparation steps[34]. A series of preparations such as acid ashing, activating, and impregnating with metals could be carried out to form a suitable catalyst for the pyrolysis process.

Rice is consumed by one-third of the world population as the primary food source. The world production of rice is about 600 million tonnes annualy. During the milling process rice, a by-product of rice husk is obtained. When 1 ton of rice is milled, it will generate approximately 200-250 of RH [35]. The tremendous amount of rice husk is the candidate to be used as a feedstock for energy supply by the combustion process in the boiler to generate steam and also yield bio-oil using the pyrolysis [36]. Rice husk ash (RHA) which predominantly composed silica is a solid residue from the combustion process in the boiler. The RHA can be utilized for many purposes, such as adsorbent [37], catalyst support [38], molecular sieve [39], fuel cell capacitors, batteries, etc. [40]. This study was developed to synthesize the RHA based catalyst for catalytic pyrolysis of RH. The synthesized catalyst was characterized using N2 adsorption-desorption, XRD, XRF spectroscopy and FTIR instrument. The temperature, catalyst addition, flow rate of nitrogen gas, and rate of heating were varied to investigate their effect on product distributions. The chemical compounds contained in bio-oil were determine using The GC-MS and FT-IR analysis.

Experimentals

Catalyst Preparation

Rice husk (RH) samples were collected from rice milling in Bantul district, Indonesia. The RH was cleaned and heated up in the oven to dry overnight at 80 °C prior to use. The samples were reduced to gain small particle size by crushing and screened to have a uniform size. The RH is burned in the furnace at 800 °C of temperature for 4 hours. Then, 10 g of the resulting RHA was activated by mixing with a certain volume of 1 N H_2SO_4 solution. The mixture was then stirred vigorously in a flat-bottom flask at reflux conditions for 6 h. When the activation process finished, the RHA was separated by filtration. Then, the activated RHA was rinsed using distilled water to neutralize and remove the sulfate ions. After that, the remaining water in the

activated RHA was eliminated by drying in the oven overnight. The NiO/RHA catalyst was synthesized by the procedure as follows: (i) 10 gr of $Ni(NO_3)_2.8H_2O$ was dissolved on 100 mL distilled water and well stirred, (ii) RHA was mixed with metals solution while heated up, (iii) the impregnation procedure was finished when the dry slurry was formed; and (iv) then, the slurry was calcined at 400°C using a heating rate of 10 °C/min for 4 hours.

2.2 Catalyst Characterization

The gas sorption analysis was used to calculate the BET surface area, total pore volumes, and average pore size diameter of the RHA and NiO-RHA/catalyst (a Quanta Chrome, NOVA10–7). The crystalline phase structure was determined by XRD. X-ray diffraction (XRD) instrument was a Shimadzu XRD X6000 instrument (Tokyo, Japan). A Ni-filtered Cu-Kα radiation (λ = 0.154060 nm) was used to record the 2θ at the range of 10-80°. The elemental compositions were calculate using the Energy Dispersive X-Ray (EDX) coupled with a scanning electron microscope (Phenom-X; Philadelphia, US).

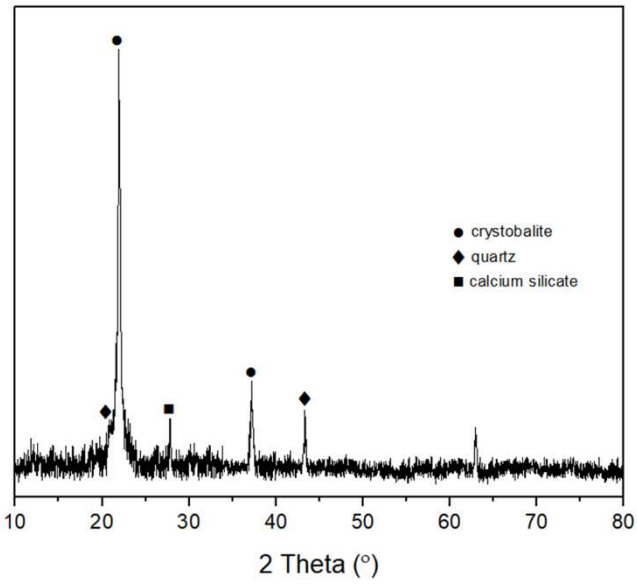
2.3 Catalytic Pyrolysis Experiments

The catalytic pyrolysis were conducted in a fixed bed reactor. The reactor was equipped with an electronic heating system, thermocouple, and a temperature-controlled. Firstly, about 25 g of RH were placed inside of the reactor. Prior to use, Nitrogen gas was flowed into the reactor to flush remaining oxygen in the reactor. Then, the reactor temperature was raised using an electronic heating system from room temperature to a selected temperature with a specific heating rate. When the selected temperature achieved, the temperature was held constantly for a certain time. The gas was condensed using a cooling water system to get the liquid products. The pyrolysis product distribution (gas, liquid and solid) was analyzed. The liquid product was analyzed to determine the compounds contained using GC-MS. Several parameters such as temperature, nitrogen gas flow rate, heating rate, and catalyst addition were varied to investigate the composition of catalytic pyrolysis products.

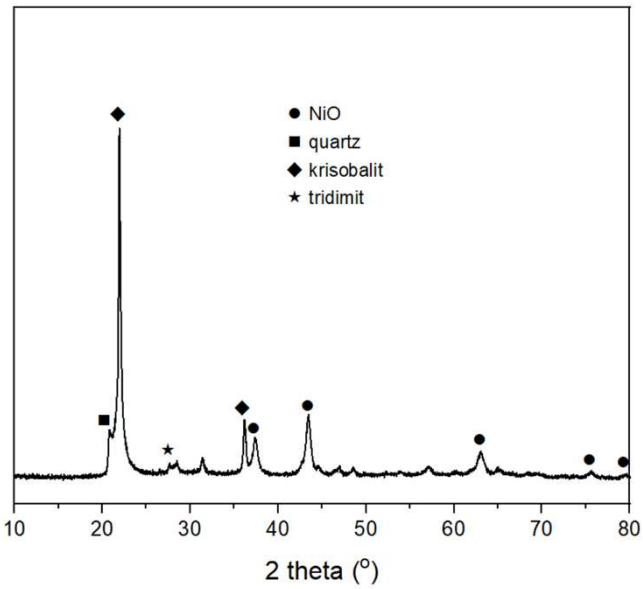
Results and Discussion

Catalyst Characterization

The rice husk ash (RHA) and NiO/RHA catalyst were characterized using the XRD instrument to analyze the crystallinity structure. Figure 1 exhibits the identification of the XRD pattern. Based on the XRD pattern of RHA, several peaks represent different crystalline phases present in the sample. The intense peaks at 2θ around 21° indicate the presence of crystobalite, a high-temperature form of silica. The sharpness and intensity suggest a significant quantity of this phase. The peaks at 2θ around 26° and 50° correspond to quartz, a naturally occurring crystalline form of silica. The presence of quartz indicates that some of the silica did not convert into other forms during the combustion of the rice husk. The peaks at 2θ = 8.1°, 9.4°, 13.1°, 15.6°, 20.3°, and 21.1–23.2° are identified as the presence of calcium silicate. Based on the XRD pattern, the crystobalite and quartz phases were containing on the RHA, with minor contributions from calcium silicate. This crystallization typically occurs when rice husk ash is prepared at high temperatures, and the transformation of amorphous silica into crystalline forms like crystobalite and quartz takes place. The presence of calcium silicate may result from impurities materials during combustion.



(a)

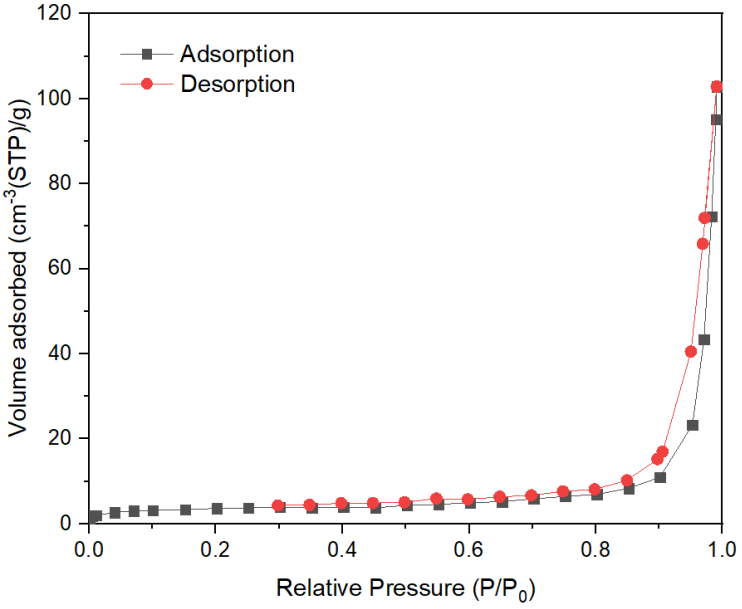


(b)

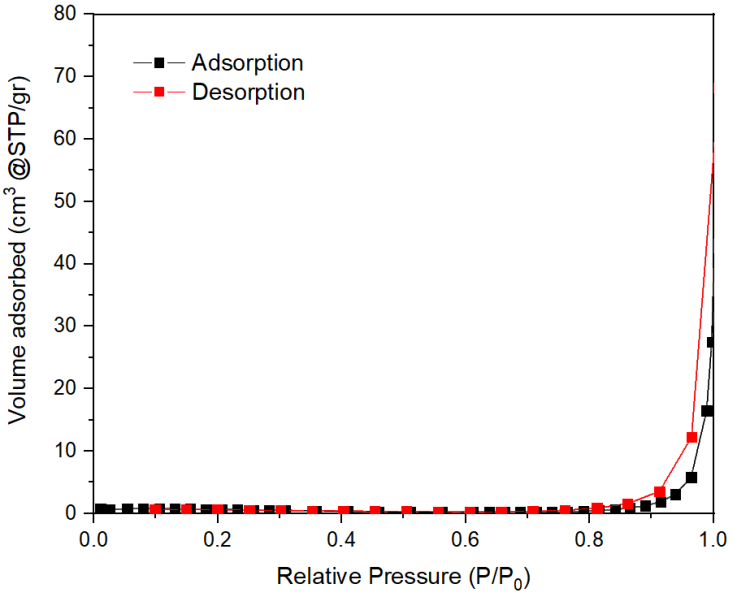
Figure 1. Diffractograms for: (a) RHA; and (b) NiO-RHA catalyst.

Figure 1 also showed several diffraction peaks at various 2θ angles the XRD result on the NiO-RHA catalyst sample. Diffraction peaks from NiO appear at 2θ around 37°, 43°, 63°, and 75 indicated the presence of crystalline NiO phase in the sample. The quartz peaks are detected at 2θ around 20.8° and 50°. Quartz is a common component in rice husk ash. The peaks appear at 2θ around 22° and 43° associated with the cristobalite structure which is one of the polymorphs of silica that often forms in silica-containing materials such as rice husk ash at high temperatures. Moreover, the tridymite peak appears at 2θ around 26.6°. Tridymite is another silica polymorph formed at high temperatures and typically found in ash or other silica-containing materials. The XRD pattern indicates that NiO is likely in a stable crystalline phase, while the silica components from the rice husk ash provide support or a structural framework for the catalyst.

Figure 2 presents the gas sorption analysis of rice husk ash and NiO-RHA catalyst. Figure 2 (a) shows that the isotherm curve of RHA corresponds to Type IV isotherm according to IUPAC classification. Based on the shape of the curve in Figure 2 (a), it appears that the isotherm of RHA is similar to a Type IV adsorption isotherm curves characterize mesoporous materials. Mesoporous materials have a pore size of 2-50 nm. The adsorption-desorption isotherm curve is characterized by a wide-open hysteresis loop and indicates the phenomenon of capillary condensation and incomplete evacuation in the pores of the material. The isotherm curve of NiO-RHA catalyst in Figure 2(b), shows the characteristics of Type IV isotherm as shown in RHA material.



(a)



(b)

Figure 2. The Gas Sorption Analysis of : (a) RHA; and (b) NiO-RHA catalyst

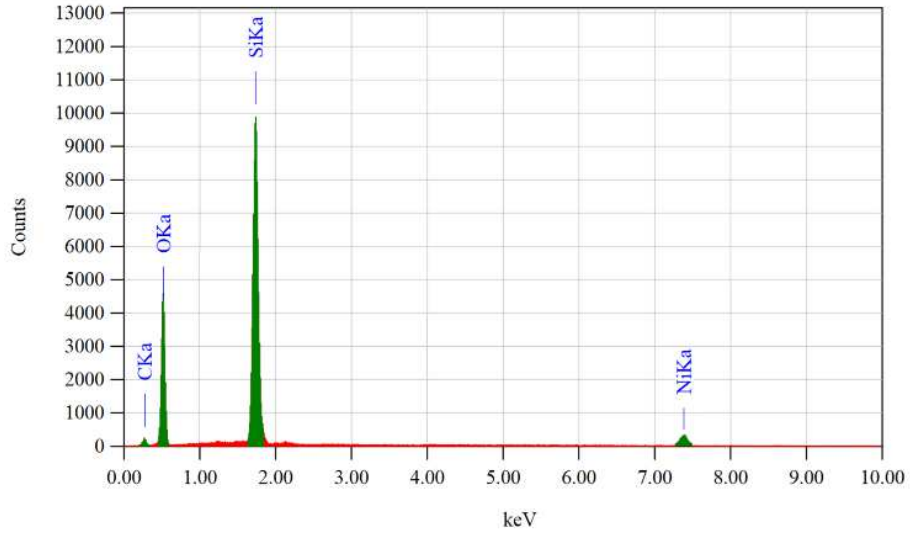
The calculation of BET surface area, total pore volumes and pore size diameter were presented in Table 1. The increase in surface area and total pore volume due to the attachment of NiO indicates that the catalyst has more active sites per unit area. Smaller pore size can affect the

diffusion of reactants and products in the pores, which has the potential to affect catalytic efficiency and selectivity.

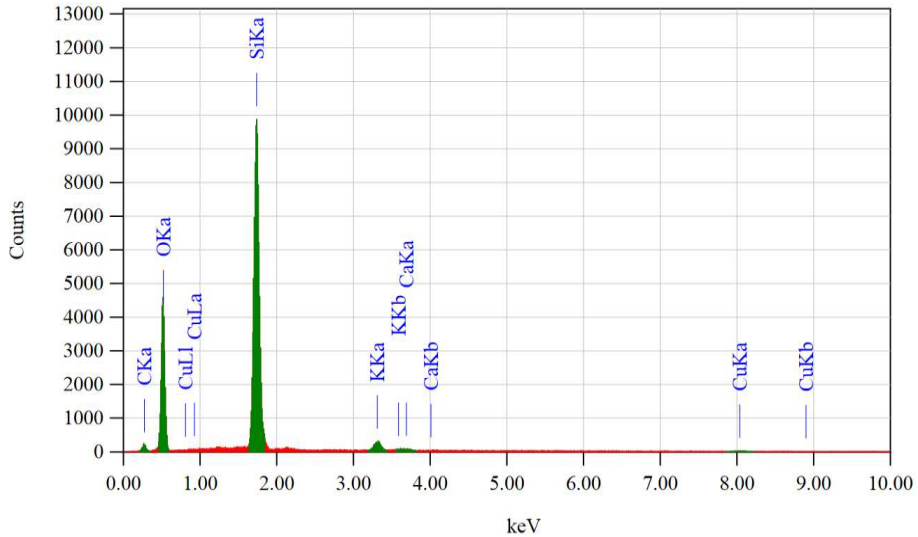
Table 1. BET surface area, total pore volumes, and pore size diameter of Rice Husk Ash and NiO-RHA catalyst.

Materials	BET Surface Area (m^2/g)	total pore volumes (m^3/g)	pore size diameter (nm)
Rice Husk Ash	1,510	0.1055	13.98
NiO-RHA catalyst	3.140	0.1042	6.64

The compositions of all samples were determined using EDX analysis. The results indicated that the RHA was mainly composed of SiO_2 and Al_2O_3. Meanwhile, the existence of NiO was detected on NiO/RHA catalyst with a value of 9.42%



(a)



(b)

Figure 3. The Elemental Compositions of : (a) RHA; and (b) NiO-RHA catalyst.

Pyrolysis Experiments

Influence of Temperature

The temperatures were arranged between 400 to 600 °C. The other parameters were set constant in a 10 °C/min of heating rate, 5 wt.% of catalyst amount and 300 cm^3/min of N_2 gas flow rate. The temperature effect on pyrolysis product distributions were shown in Figure 4. The gaseous and liquid yields were achieved at 45 and 29% at a temperature of 600 °C. It concluded that the gaseous and liquid yields increased when the temperature was enhanced. Meanwhile, the solid product yield of liquid reduced with increasing temperature. The minimum yield was obtained at 18%. At raised temperature, the pyrolysis process will generate more quantity of CO and H_2, which be a consequence of reducing liquid product yield. Furthermore, at high temperatures, it will enhance the secondary decomposition of char and pyrolysis vapours which result in more gas product and non-condensable gas.

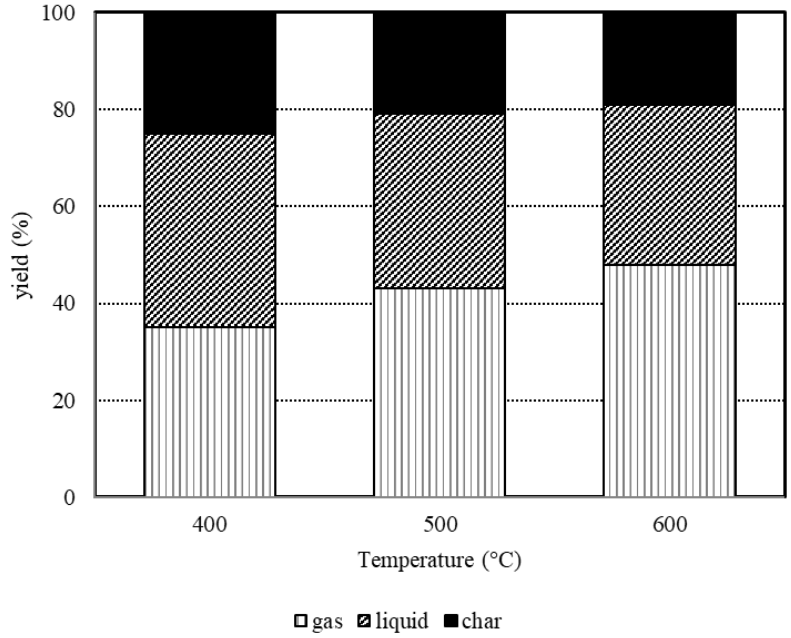


Figure 4. Influence of Temperature on Product Distributions.

Influence of Nitrogen Gas Flow Rate

Nitrogen gas flow rate plays an important role during the catalytic pyrolysis of biomass. The inert conditions need to maintain as an oxygen-free environment ensuring thermal decomposition can occured. Figure 5 depicts the product yield (gas, liquid, and char) from the catalytic pyrolysis of biomass using NiO-RHA catalyst at different Nitrogen gas flow rates (100, 200, and 300 cm^3/mins).

The liquid yields were achieved at 35 and 42% when the N_2 gas flow rates were increased from 100 to 200 mL/min, respectively. The liquid yield reaches 47% at a 300 mL/mins N_2 gas flow rate. The contrary result was obtained on char product yield. The char yield reduced from 29% to 19% when the flow rate was switched from 100 to 200 mL/min. At a 300 mL/min of nitrogen gas flow rate, the lowest value of char yield was achieved 14%. Meanwhile, the gas yield was achieved at 36 and 39% at 100 and 200 mL/min of flow rate, respectively. Furthermore, the gas product yield reaches a maximum value of 49% when a 300 mL/min of flow rate is applied. In the pyrolysis process, the inert gases were flowed to purge the hot pyrolysis vapours, so the residence times of pyrolysis vapours were shorter. Thus, the increase of the inert gases could reduce the possibility of secondary reactions such as polymerization, condensation, and vapour

thermal cracking. The removal of hot vapours of pyrolysis into the condensation section would be reduced at lower gas flow rates.

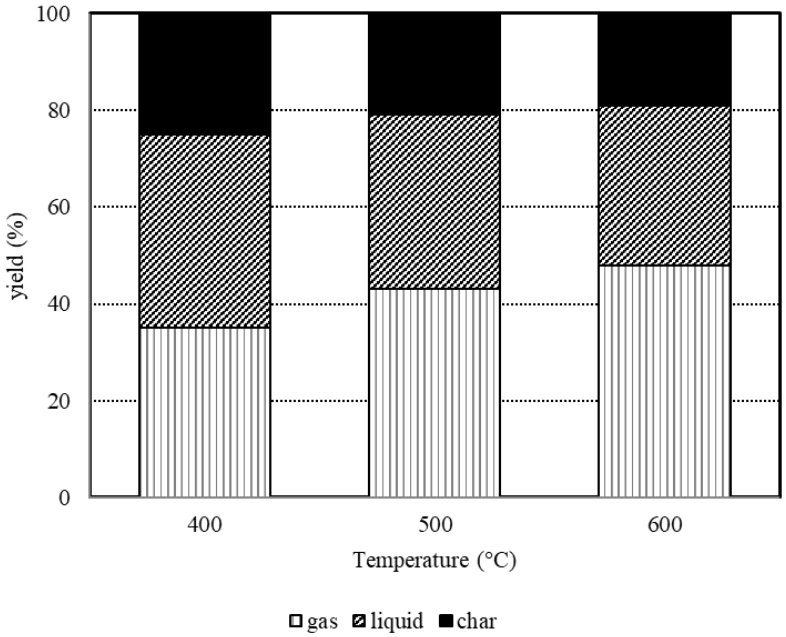


Figure 5. Influence of Nitrogen Gas Flow Rate on Product Yield.

Influence of Heating Rate

The product yield during catalytic pyrolysis using NiO-RHA catalyst was influenced the heating rate as shown in Figure 5. By controlling the heating rate and cooling of primary vapors, the secondary reactions could be reduced so that the liquid yield would be enhanced and avoid the reduction of bio-oil quality. When the low heating rate is applied, it will lead to higher char yields. The increase of liquid yields was found from 36% to 44% when the heating rate changes from 10 to 20 °C/min, respectively. Furthermore, the highest liquid yield was reached at 48% at a 30 °C/min of heating rate. An increase in gas yields occurred from 33% to 36% when the heating rate was switched from 10 to 20 °C/min. Thus, the gas product yield was achieved maximum at 40% when applying a 30 °C/min of heating rate. However, at a 30 °C/min of heating rate, yield of char reached a minimum value at 16%.

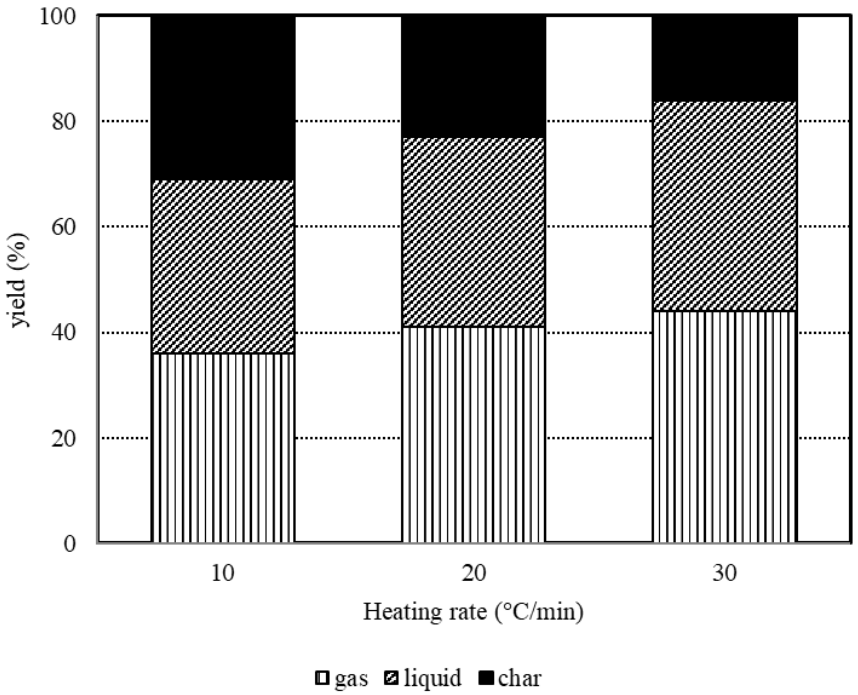


Figure 6. Influence of Heating Rate on Product Yield.

Influence of Catalyst

Bio-oil consists of many oxygenated compounds that can be applied directly as fuel in the boiler in the power plant. Nevertheless, the quality of bio-oil should be upgraded if it is applied as a substitute for transportation fuel. The upgrading process can be done by catalytic pyrolysis to produce more aromatic or light hydrocarbons. The presence of catalysts can enhance the bio-oil quality and change the yield in the pyrolysis process. The formation of valuable products such as hydrocarbons, esters, phenols, and furans. can promote by applying catalysts during pyrolysis. The catalysts will encourage many reactions, i.e. cracking, dehydrogenation, dehydration, decarboxylation, and decarbonation. The significant effect of increasing the liquid and gas product yield from the pyrolysis process due to using the RHA catalyst can be seen in Figure 6. The maximum liquid and gas product yield was obtained at 51 and 39%, respectively. Meanwhile, the char yield was obtained at 10%. The cracking with catalyst can produce additional liquid and gas products.

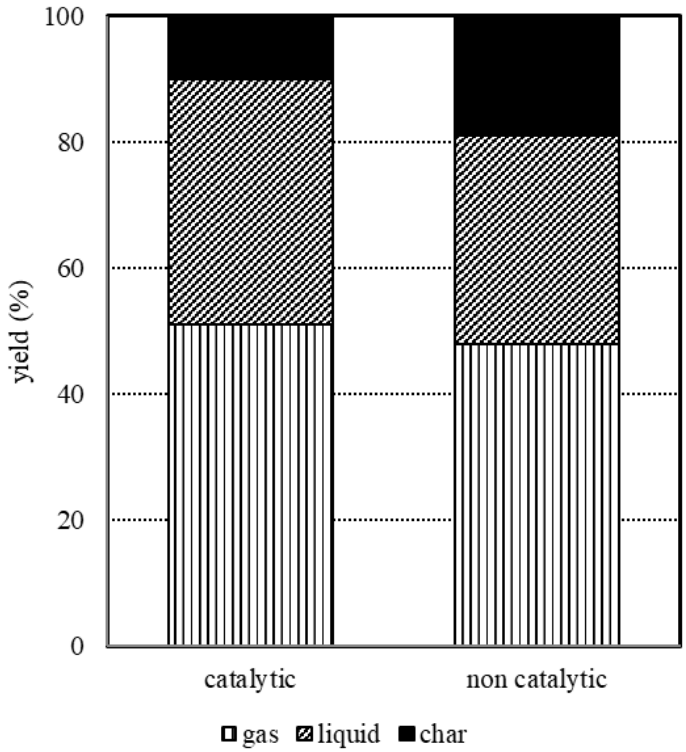


Figure 7. Influence of Catalyst on Product Yield.

3.3 Bio-oil Products Chemical Composition

The GC-MS instrument was used to determine the chemical components on bio-oil. Table 2 listed the major components found on bio-oil products during non-catalytic and catalytic pyrolysis of rice husk.

Table 2. The major components of bio-oil products are from catalytic and non-catalytic pyrolysis of rice husk.

Retention time	Chemical name	Formula	Peak areas (%)	
			non-catalytic	catalytic
3.616	Acetic acid	$C_2H_4O_2$	7.88	4.74
8.390	Levoglucosan	$C_6H_{10}O_5$	3.53	1.47
10.097	Phenol	C_6H_6O	21.84	16.85
10.225	Tetrahydro-2-furanmethanol	$C_5H_{10}O_2$	2.18	4.86
12.554	o-cresol/2-Methylphenol	C_7H_8O	8.16	5.67
12.953	Guaiacol/2-Methoxyphenol	$C_7H_8O_2$	7.40	3.95
13.428	p-creosol/2-Methoxy-p-cresol	C_7H_8O	3.20	2.46
19.530	1.3-Cyclopentanedione	$C_5H_6O_2$	4.34	2.48
20.978	Syringol	$C_8H_{10}O_3$	8.58	4.34
21.802	2.5-Dimethylfuran	C_6H_8O	3.29	5.04
22.776	1-Tetradecene	$C_{14}H_{28}$	n.a.	3.53
25.412	1-Pentadecene	$C_{15}H_{30}$	n.a.	6.77
25.682	Heptadecane	$C_{17}H_{38}$	n.a.	4.89
25.723	5-Methyl-2(5H)-furanone	$C_5H_6O_2$	1.88	3.05
35.032	Furfural	$C_5H_4O_2$	6.87	7.85

The bio-oil showed a complex mixture of organic compounds from many chemical groups, *i.e.*, phenols, aromatic hydrocarbon, furans, ketones, esters, and other substances. At high temperature, the cellulose, hemicellulose, and lignin on rice husk would be degraded to form organic compounds during the pyrolysis process. The distributions of many chemical groups from catalytic and non-catalytic pyrolysis were presented in Figure 8.

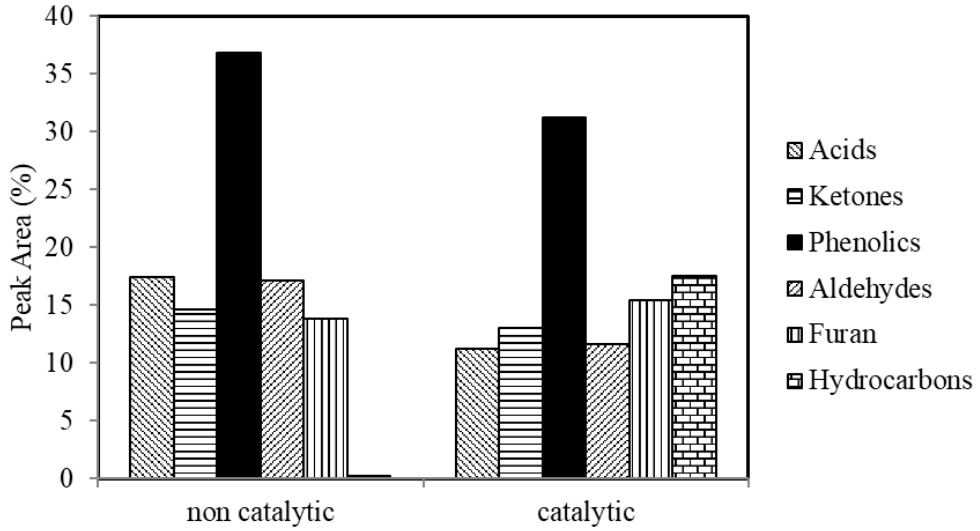
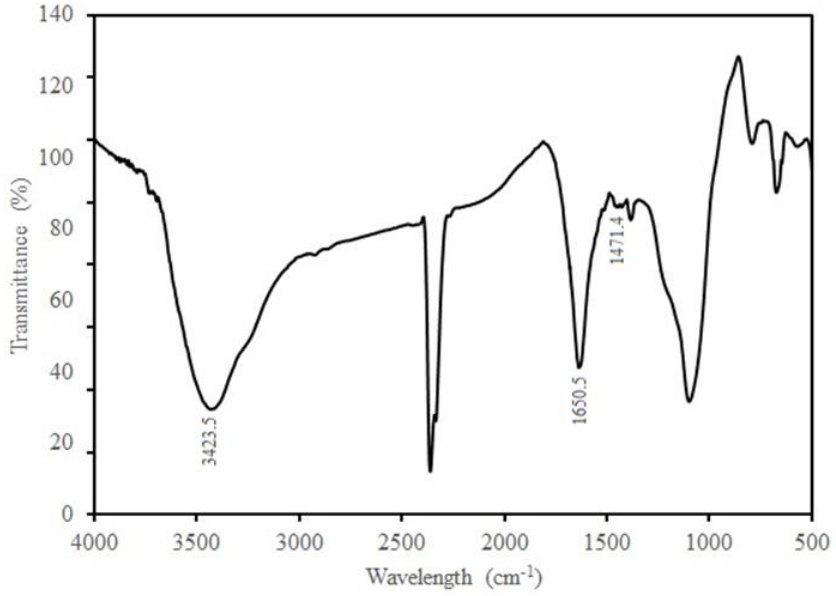


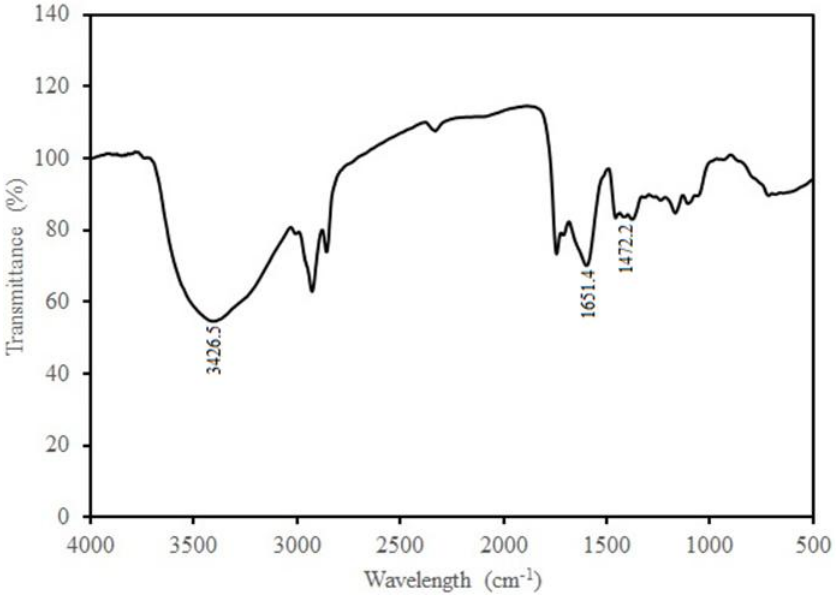
Figure 8. The GC/MS analysis of bio-oil products.

Based on Figure 7, several organic compounds were found similarly in non-catalytic and catalytic pyrolysis. The organic compounds contained in bio-oil were formed from the degradation of cellulose, hemicellulose, and lignin. The degradation of lignin produced more aromatic hydrocarbons such as benzene, phenols, cresols, and substituted phenols. Decomposition of cellulose generates alcohol, furfural keton and esters. Meanwhile, the acids could be formed from the deacetylation of the hemicelluloses. However, the presence of catalyst promoted the forming of more hydrocarbons in the bio-oil as well as reducing the acids. The alcohol and ester groups were also detected in the bio-oil.

To identify the functional groups on bio-oil, the FT-IR spectra was applied. FTIR spectra of bio-oils were shown in Figure 8. The bio-oil FTIR spectra between catalytic and non-catalytic pyrolysis showed a similar result. The OH stretching vibrations at the wavenumber between 3200 and 3600 cm^{-1} attributed the existence of phenols, alcohols, and/or esters in the bio-oil. The ketone and aldehyde groups were identified between 1640 and 1820 cm^{-1}, respectively. The presence of aromatic compounds was associated with the wavenumber between 1460 and 1480 cm^{-1}, which related to vibration stretching C = C aromatic. Based on GC-MS and FT-IR analysis, it can be concluded that the bio-oil contains the aromatic, carboxylic acids, ketone, aldehyde, alcohols, and esters during catalytic and non-catalytic pyrolysis.



(a)



(b)

Figure 9. The bio-oils FTIR spectra: (a) non-catalytic; and (b) catalytic.

Conclusion

The NiO-RHA catalysts were successfully synthesized from RHA. The catalyst was prepared by impregnating nickel oxide on rice husk ash (RHA), and its properties were characterized using techniques such as nitrogen adsorption-desorption, XRD, and EDX. The NiO-RHA catalysts were tested for catalytic pyrolysis of rice husk. The use of NiO/RHA catalyst led to increased liquid bio-oil yield and decreased char yield. The optimal process conditions results were achieved at a temperature of 600°C, a nitrogen gas flow rate of 300 cm^3/min, and a heating rate of 30 °C/min. The presence of the catalyst promoted the formation of valuable compounds such as hydrocarbons, esters, phenols, and furans in the bio-oil, improving its quality. This study highlights the potential of NiO/RHA catalyst as an effective catalyst for enhancing bio-oil production from rice husk.

Acknowledgments

This research was financially supported by the Direktorat Penelitian dan Pengabdian Masyarakat Universitas Islam Indonesia through Penelitian Unggulan scheme year 2017.

Author Contributions: Arif Hidayat: Conceptualization, methodology, analysis, writing, editing, Bachrun Sutrisno.; administration and editing. Is Fatimah; supervision and validation. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] O. Azeta, A.O. Ayeni, O. Agboola, F.B. Elehinafe, A review on the sustainable energy generation from the pyrolysis of coconut biomass, Scientific African 13 (2021) e00909.
[2] F. Campuzano, R.C. Brown, J.D. Martínez, Auger reactors for pyrolysis of biomass and wastes, Renewable and Sustainable Energy Reviews 102 (2019) 372-409.
[3] Y. Liu, S. Wu, H. Zhang, R. Xiao, Fast pyrolysis of torrefied holocellulose for producing long-chain ether precursors in a fluidized bed, Bioresource Technology 341 (2021) 125770.
[4] A. Al-Rumaihi, M. Shahbaz, G. McKay, H. Mackey, T. Al-Ansari, A review of pyrolysis technologies and feedstock: A blending approach for plastic and biomass towards optimum biochar yield, Renewable and Sustainable Energy Reviews 167 (2022) 112715.
[5] L.D.B. Pestaño, W.I. Jose, Production of Solid Fuel by Torrefaction Using Coconut Leaves as Renewable Biomass, International Journal of Renewable Energy Development 5(3) (2016).
[6] A. Hidayat, M.A. Adnan, H. Dewajani, Production Biofuels from Palm Empty Fruit Bunch by Catalytic Pyrolysis Using Calcined Dolomite, Materials Science Forum, Trans Tech Publ, 2021, pp. 153-158.
[7] M.S.A. Bakar, J.O. Titiloye, Catalytic pyrolysis of rice husk for bio-oil production, Journal of analytical and applied pyrolysis 103 (2013) 362-368.
[8] B. Sutrisno, A. Hidayat, Upgrading of bio-oil from the pyrolysis of biomass over the rice husk ash catalysts, IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2016, p. 012014.
[9] M. Ferreira, B. Oliveira, W. Pinheiro, N. Correa, L. França, N. Ribeiro, Generation of biofuels by slow pyrolysis of palm empty fruit bunches: Optimization of process variables and characterization of physical-chemical products, Biomass and Bioenergy 140 (2020) 105707.
[10] V. Balasundram, K.K. Zaman, N. Ibrahim, R.M. Kasmani, R. Isha, M.K.A. Hamid, H. Hasbullah, Catalytic upgrading of pyrolysis vapours over metal modified HZSM-5 via in-situ pyrolysis of sugarcane bagasse: effect of nickel to cerium ratio on HZSM-5, Journal of analytical and applied pyrolysis 134 (2018) 309-325.
[11] Y. Gao, Y. Yang, Z. Qin, Y. Sun, Factors affecting the yield of bio-oil from the pyrolysis of coconut shell, SpringerPlus 5 (2016) 1-8.
[12] E. Salehi, J. Abedi, T. Harding, Bio-oil from sawdust: effect of operating parameters on the yield and quality of pyrolysis products, Energy & fuels 25(9) (2011) 4145-4154.
[13] A.S. Paul, N.L. Panwar, B.L. Salvi, S. Jain, D. Sharma, Experimental investigation on the production of bio-oil from wheat straw, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects (2020) 1-16.
[14] M.R. Younis, M. Farooq, M. Imran, A.H. Kazim, A. Shabbir, Characterization of the viscosity of bio-oil produced by fast pyrolysis of the wheat straw, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 43(15) (2021) 1853-1868.
[15] Y. Wang, A. Akbarzadeh, L. Chong, J. Du, N. Tahir, M.K. Awasthi, Catalytic pyrolysis of lignocellulosic biomass for bio-oil production: A review, Chemosphere 297 (2022) 134181.
[16] V. Anand, R. Gautam, R. Vinu, Non-catalytic and catalytic fast pyrolysis of Schizochytrium limacinum microalga, Fuel 205 (2017) 1-10.
[17] B. Biswas, R. Singh, B.B. Krishna, J. Kumar, T. Bhaskar, Pyrolysis of azolla, sargassum tenerrimum and water hyacinth for production of bio-oil, Bioresource Technology 242 (2017) 139-145.

[18] S. Wang, Q. Wang, X. Jiang, X. Han, H. Ji, Compositional analysis of bio-oil derived from pyrolysis of seaweed, Energy Conversion and Management 68 (2013) 273-280.
[19] S. Maisano, F. Urbani, N. Mondello, V. Chiodo, Catalytic pyrolysis of Mediterranean sea plant for bio-oil production, International Journal of Hydrogen Energy 42(46) (2017) 28082-28092.
[20] A.K. Vuppaladadiyam, S.S.V. Vuppaladadiyam, A. Awasthi, A. Sahoo, S. Rehman, K.K. Pant, S. Murugavelh, Q. Huang, E. Anthony, P. Fennel, Biomass pyrolysis: A review on recent advancements and green hydrogen production, Bioresource Technology (2022) 128087.
[21] A. Hidayat, M.A. Adnan, A. Chafidz, Catalytic Pyrolysis of Palm Empty Fruit Bunch over Activated Natural Dolomite Catalyst: Product Distribution and Product Analysis, Materials Science Forum, Trans Tech Publ, 2020, pp. 111-116.
[22] T. Cordero-Lanzac, R. Palos, J.M. Arandes, P. Castaño, J. Rodríguez-Mirasol, T. Cordero, J. Bilbao, Stability of an acid activated carbon based bifunctional catalyst for the raw bio-oil hydrodeoxygenation, Applied catalysis B: environmental 203 (2017) 389-399.
[23] S.R. Khan, M. Zeeshan, A. Ahmed, S. Saeed, Comparison of synthetic and low-cost natural zeolite for bio-oil focused pyrolysis of raw and pretreated biomass, Journal of Cleaner Production 313 (2021) 127760.
[24] L.M. López-Renau, L. García-Pina, H. Hernando, G. Gómez-Pozuelo, J.A. Botas, D.P. Serrano, Enhanced bio-oil upgrading in biomass catalytic pyrolysis using KH-ZSM-5 zeolite with acid-base properties, Biomass Conversion and Biorefinery 11 (2021) 2311-2323.
[25] S. Du, D.P. Gamliel, J.A. Valla, G.M. Bollas, The effect of ZSM-5 catalyst support in catalytic pyrolysis of biomass and compounds abundant in pyrolysis bio-oils, Journal of analytical and applied pyrolysis 122 (2016) 7-12.
[26] E.B. Inaloo, M. Saidi, Catalytic pyrolysis of olive pomace for biofuel production: Application of metal oxide-modified zeolite catalysts, Biomass and Bioenergy 177 (2023) 106947.
[27] R. Singh, N. Chakinala, K. Mohanty, A.G. Chakinala, Catalytic upgrading of biomass pyrolysis vapors for selective production of phenolic monomers over metal oxide modified alumina catalysts, Journal of Environmental Chemical Engineering 11(6) (2023) 111518.
[28] W. Choi, H. Jo, J.-W. Choi, D.J. Suh, H. Lee, C. Kim, K.H. Kim, K.-Y. Lee, J.-M. Ha, Stabilization of acid-rich bio-oil by catalytic mild hydrotreating, Environmental Pollution 272 (2021) 116180.
[29] P. Yan, I.N. Azreena, H. Peng, H. Rabiee, M. Ahmed, Y. Weng, Z. Zhu, E.M. Kennedy, M. Stockenhuber, Catalytic hydropyrolysis of biomass using natural zeolite-based catalysts, Chemical Engineering Journal 476 (2023) 146630.
[30] A. Ahmed, S.R. Khan, M. Zeeshan, Application of low-cost natural zeolite catalyst to enhance monoaromatics yield in co-pyrolysis of wheat straw and waste tire, Journal of the Energy Institute 105 (2022) 367-375.
[31] J. Milovanović, R. Luque, R. Tschentscher, A.A. Romero, H. Li, K. Shih, N. Rajić, Study on the pyrolysis products of two different hardwood lignins in the presence of NiO contained-zeolites, Biomass and Bioenergy 103 (2017) 29-34.
[32] Y. Kar, Catalytic cracking of pyrolytic oil by using bentonite clay for green liquid hydrocarbon fuels production, Biomass and Bioenergy 119 (2018) 473-479.
[33] H. Li, Y. Wang, N. Zhou, L. Dai, W. Deng, C. Liu, Y. Cheng, Y. Liu, K. Cobb, P. Chen, Applications of calcium oxide–based catalysts in biomass pyrolysis/gasification–a review, Journal of Cleaner Production 291 (2021) 125826.
[34] V.R. Madduluri, K.K. Mandari, V. Velpula, M. Varkolu, S.R.R. Kamaraju, M. Kang, Rice husk-derived carbon-silica supported Ni catalysts for selective hydrogenation of biomass-derived furfural and levulinic acid, Fuel 261 (2020) 116339.
[35] S.S. Hossain, P. Roy, C.-J. Bae, Utilization of waste rice husk ash for sustainable geopolymer: A review, Construction and Building Materials 310 (2021) 125218.
[36] W.A. Wibowo, R.B. Cahyono, R. Rochmadi, A. Budiman, Thermogravimetric Analysis and Kinetic Study on Catalytic Pyrolysis of Rice Husk Pellet using Its Ash as a Low-cost In-situ Catalyst, International Journal of Renewable Energy Development 11(1) (2022) 207-219.
[37] K. Swarnalakshmi, P. Chinnaiyan, S. Nivetha, A.S. Nair, Use of rice husk ash as an adsorbent to remove contaminants in water and comparison with advanced oxidation process–a study, Materials Today: Proceedings 5(11) (2018) 24248-24257.

[38] Z. Teng, S. Huang, L. Fu, H. Xu, N. Li, Q. Zhou, Study of a catalyst supported on rice husk ash for NO reduction with carbon monoxide, Catalysis Science & Technology 10(5) (2020) 1431-1443.
[39] J. Madhu, A. Santhanam, M. Natarajan, D. Velauthapillai, CO2 adsorption performance of template free zeolite A and X synthesized from rice husk ash as silicon source, RSC Advances 12(36) (2022) 23221-23239.
[40] L. Zhou, H. Yang, H. Wu, M. Wang, D. Cheng, Catalytic pyrolysis of rice husk by mixing with zinc oxide: Characterization of bio-oil and its rheological behavior, Fuel Processing Technology 106 (2013) 385-391.