UNIVERSITI PUTRA MALAYSIA

PRODUCTION OF BIO-OIL VIA HYDROTHERMAL LIQUEFACTION OF EMPTY FRUIT BUNCH USING ZEOLITE AND MCM-41 BASED CATALYSTS

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FS 2022 22

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

June 2020

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in Fulfillment of the requirement for the degree of Doctor of Philosophy

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Chairman : Prof. Datuk. ChM. Ts. Taufiq Yap Yun Hin, PhD
Faculty : Science

Biomass is one of the renewable energy that has been revealing its potential as a substituent for natural fossil fuel recently. Nowadays, converting biomass via hydrothermal liquefaction appears to be another alternative to obtain valuable high energy products and chemical. In this study, oil palm empty fruit bunch (EFB) has been chosen as the source of biomass feedstock for conversion of biomass to bio-oil using HZSM-5 (zeolite) and MCM-41 (Mobil Composition of Matter number 41) as a based catalysts. The different composition of metal promoter barium (Ba), nickel (Ni), lanthanum (La) and cerium (Ce) either mono or bimetal were impregnated into zeolite (denoted as CHZSM5) and further investigated. High acidity properties of Ba and Ni modified CHZSM5 found to be the most effective in catalysing the hydrothermal liquefaction of EFB. Besides, the high surface area and volume ratio of combined two metal promoter (Ba1La2, Ba2Ni1 and Ba2La1/CHZSM5) catalysts were the reasons in the increment in the acidic sites and eventually enhanced the catalytic activity in hydrothermal liquefaction of EFB. Other than that, hierarchical zeolite has been produced with the presence of cetyltrimethylammonium bromide (CTAB) as a surfactant and *n*-alkane (*n*-hexane, *n*-octane, *n*-decane and *n*-dodecane) as swelling agent to tailor the formation of hierarchical zeolite with large pore. 1.5 molar ratios of *n*-alkane significantly reduced the size of nanocrystals formed compared to 1.1 *n*-alkanes, implying high acidity strength of hierarchical zeolite positively influenced by the size of nanocrystal and impactful in catalyst's perfomance. This study also revealed the ratio of silica to aluminum, Si/Al = 0.03 gave a great influence to the surface area, pore volume and pore diameter of the synthesized MCM-41 (denoted as CMCM Si/Al 0.03) and proportionally increase the acidity of the final catalyst. The addition of active metal Ni into CMCM Si/Al 0.03 rendered the greater dispersion of the crystals and at the same time induces the acidity of the catalyst. As mentioned above, high acidity

and high textural properties of the synthesised catalysts improved the quality of the obtained bio-oil in the catalytic hydrothermal liquefaction of EFB with less oxygenated compounds.

Abstrak tesis yang dikemukan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

PENGHASILAN BIO-MINYAK MELALUI PENCECAIRAN HIDROTERMA TANDAN BUAH KOSONG MENGGUNAKAN ASAS MANGKIN ZEOLIT DAN MCM-41

Oleh

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Biojisim adalah salah satu tenaga boleh diperbaharui yang telah didedahkan potensinya sebagai gantian bahan api fosil semulajadi baru-baru ini. Pada masa kini, penukaran biojisim melalui pencecairan hidroterma telah menjadi salah satu alternatif untuk memperolehi produk tenaga tinggi dan bahan kimia yang berharga. Dalam kajian ini, tandan buah kosong kelapa sawit (EFB) telah dipilih sebagai sumber biojisim bahan mentah untuk penukaran biojisim kepada bio-minyak menggunakan asas mangkin HZSM-5 (zeolit) dan MCM-41 (komposisi mobil bagi jirim nombor 41). Perbezaan komposisi logam pendorong barium (Ba), nickel (Ni), lanthanum (La) dan cerium (Ce)) samada secara tunggal atau dwi-logam telah di isitepuan kedalam zeolit (dilambangkan sebagai CHZSM5) dan disiasat selanjutnya. Ciri-ciri keasidan yang tinggi pada Ba dan Ni mengubahsuai CHZSM5 telah dilihat sebagai paling efektif dalam memangkin pencecairan hidroterma EFB. Di samping itu, kawasan permukaan yang tinggi dan nisbah isipadu gabungan dua logam pendorong mangkin (Ba1La2, Ba2Ni1 and Ba2La1/CHZSM5) adalah penyebab kepada peningkatan tapak asid dan seterusnya menambah aktiviti pemangkinan dalam pencecairan hidroterma EFB. Selain daripada itu, zeolit hierarki telah dihasilkan dengan kehadiran cetyltrimethylammonium bromide (CTAB) sebagai surfaktan dan *n*-alkana (*n*-heksana, *n*-oktana, *n*-dekana dan *n*-dodekana) sebagai agen pengembang untuk membina pembentukan zeolit hierarki berliang besar. 1.5 nisbah molar *n*-alkana secara ketara merendahkan saiz nanokristal yang dibentuk berbanding dengan 1.1 *n*-alkana, menandakan kekuatan keasidan yang tinggi pada zeolit hierarki secara positifnya dipengaruhi oleh saiz nanokristal dan memberi impak tinggi kepada prestasi mangkin. Kajian ini juga mendedahkan nisbah silica kepada aluminum, Si/Al = 0.03 memberi kesan yang besar kepada luas kawasan permukaan, isipadu liang dan diameter liang MCM-41 yang disintesis (dilambangkan sebagai CMCM Si/Al 0.03) dan meningkatkan keasidan mangkin akhir secara berkadar.

Penambahan logam aktif Ni ke dalam CMCM Si/Al 0.03 memberikan penyelerakan kristal yang terbaik dan pada masa yang sama mencetuskan keasidan mangkin. Seperti yang dinyatakan di atas, keasidan yang tinggi dan sifat tekstur yang tinggi pada mangkin yang disintesis telah meningkatkan kualiti bio-minyak yand diperolehi dalam pencecairan hidroterma EFB dengan pengurangan sebatian beroksigen.

ACKNOWLEDGEMENTS

In the name of Allah, the Most Gracious and the Most Merciful

First and foremost, I am thankful to almighty Allah s.w.t. for giving me His blessing, strength, knowledge, ability and opportunity throughout this research work. Special thanks to my respected "father", teacher and supervisor, Prof. Datuk. ChM. Ts. Dr. Taufiq Yap Yun Hin, for his continuous guidance, inspiration, encouragement and assistance in completing my PhD study. His valuable advice and humanitarian values have had a significant impact on my morale and skills in conducting my research. No matter how bad my situation was before, he always gave me the opportunities and believed in me to complete my study to the finishing line.

I also would like to convey my deepest gratitude to Prof. ChM. Dr. Zulkarnain Zainal, Dr Kamaliah Hj Sirat and Prof. Ir. Dr. Suzana Yusup (UTP) as my co-supervisors for their kind supervision and excellent research assistant during carrying out my research.

My profound gratitude also goes to my late father (Hj. Nawi @ Mohamed), mother (Rohani Mat Abd. Ghani), parents in law (Hj. Md Nasir and late Hjh. Normala Juki), thank you for being a loving parent who has always been there for me. Because of their prayers, Allah gave me the strength not to give up easily. My deepest gratitude also goes to my soul partner (Izrul Azmi), daughters (Khayla and Maream), brother (Jamsuri Nawi) and other family members for their support and endless prayers throughout my studies. Without their support, I would not have been able to get through it.

Not forgotten, thanks to all my colleagues and friends, especially Dr Nurul Asikin Mijan, Dr Siow Hwa Teo, Mr. Surahim and other members of Catalysis Science and Technology Research Centre (PutraCAT), staff and technicians at the Department of Chemistry, Faculty of Science, Universiti Putra Malaysia for their help and imparting knowledge during my research studies. All of you are always in my prayers and hold a special place in my heart. Last but not least, I also would like to thank Ministry of Higher Education (MOHE) for the financial support throughout my research journey. This is not the end, but a new beginning in the journey of knowledge.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

BET	Brunauer – Emmer – Teller
CHZSM5	Commercial zeolite ZSM-5
CMCM	Calcined MCM-41
CTAB	Cetyltrimethylammonium bromide
EFB	Empty Fruit bunch
FESEM	Field Emission Scanning Electron Microscopy
GCMS	Gas Chromatography Mass Spectrometer
ICP-OES	Induced Coupled Plasma – Optical Emission Spectroscopy
JCPDS	Joint Committee of Powder Diffraction Standards
MFI	Modernite Framework Inverted
nC$_6$	*n*-hexane
nC$_8$	*n*-octane
nC$_{10}$	*n*-decane
nC$_{12}$	*n*-dodecane
SEM	Scanning Electron Microscopy
Si/Al	Silica/Alumina
TPD-NH_3	Temperature Programmed Desorption of Ammonia
TPR	Temperature Programmed Reduction
XRD	X-Ray Diffraction
Mt	Million tonnes

REFERENCES

Abdulkareem-Alsultan, G., Asikin-Mijan, N., Lee, H. V., & Taufiq-Yap, Y. H. (2016). A new route for the synthesis of La-Ca oxide supported on nano activated carbon via vacuum impregnation method for one pot esterification-transesterification reaction. *Chemical Engineering Journal* (304) 61–71.

Abdullah, N., & Sulaim, F. (2013). The Oil Palm Wastes in Malaysia. Biomass Now - Sustainable Growth and Use. *Open Access.*

Adam, J., Antonakou, E., Lappas, A., Stöcker, M., Nilsen, M. H., Bouzga, A., Hustad, J.E., Øye, G. (2006). In situ catalytic upgrading of biomass derived fast pyrolysis vapours in a fixed bed reactor using mesoporous materials. *Microporous Mesoporous Material.* (96) 93–101.

Adjaye, J. D., Bakshi, N. (1995) Catalytic conversion of a biomass-derived oil to fuels nd chemicals I: model compound studies and reaction pathways. *Biomass Bioenergy.* (8) 131 – 149.

Aho, A., Kumar, N., Lashkul, A., Eränen, K., Ziolek, M., Decyk., P. (2010). Catalytic upgrading of woody biomass derived pyrolysis vapours over iron modified zeolites in a dual-fluidized bed reactor. *Fuel* (89) 1992 – 2000.

Akhtar, J., Kuang, S. K., Amin, N. S. (2010). Liquefaction of empty fruit bunch (EPFB) in alkaline hot compressed water. *Renewable Energy.* (35) 1220 – 1227.

Alipour, Z., Rezaei, M., & Meshkani, F. (2014). Effect of alkaline earth promoters (MgO, CaO, and BaO) on the activity and coke formation of Ni catalysts supported on nanocrystalline Al_2O_3 in dry reforming of methane. *Journal of Industrial and Engineering Chemistry,* (5) 2858 – 2863.

Alsultan, G. A., Asikin-Mijan, N., Lee, H. V., Albazzaz, A. S., & Taufiq-Yap, Y. H. (2017) Deoxygenation of waste cooking to renewable diesel over walnut shell-derived nanorode activated carbon supported CaO-La_2O_3 catalyst. *Energy Conversion and Management,* (151) 311–323.

Amirah, A., Mohd Hasmizan, R., Khairul Anuar, M. A. (2018) Review of metal supported on mesoporous MCM41 as catalysts for CNTs growth. *Materials Science and Engineering* (220) 1-8.

Antonakou, E. V., Lappas, A., Dimitropoulos, V. (2006) Production and characterization of bio-oil from catalytic biomass pyrolysis. *Thermal Science* (10) 151 – 160.

Ardiyanti A., Khromova S.A., Venderbosch R.H., Yakovlev V.A., Heeres H.J. (2012) Catalytic hydrotreatment of fast-pyrolysis oil using non-sulfided

bimetallic Ni-Cu catalysts on a δ-Al_2O_3 support. *Applied Catalysis B: Environmental* (117) 105–117.

Arena, U. (2012). Process and technological aspects of municipal solid waste gasification: a review. *Waste Management.* (32) 625 – 639.

Asikin-Mijan, N., Lee, H. W., Juan, J. C., Noorsaadah, A. R., Abdulkareem-Alsultan, G., Arumugam, M., Taufiq-Yap, Y. H. (2016).Waste clamshell-derived CaO supported Co and W catalysts for renewable fuels production via cracking-deoxygenation of triolein. *Journal of Analytical and Applied Pyrolysis* (120) 110-120

Auersvald, M.; Shumeiko, B.; Vrtiška, D.; Straka, P.; Staš, M.; Šimáček, P.; Blažek, J.; Kubička, D. (2019) Hydrotreatment of straw bio-oil from ablative fast pyrolysis to produce suitable refinery intermediates. *Fuel* (238) 98– 110.

Awalludin, M.F., Sulaiman, O., Hashim, R., Nadhari, W.N.A.W. (2015) An overview of the oil palm industry in Malaysia and its waste utilization through thermochemical conversion, specifically via liquefaction. *Renewable Sustainable Energy Reviews* (50) 1469 – 1484.

Balasundram, V., Ibrahim, N., Kasmani, R. M., Isha, R., Hamid, M. K. A., Hasbullah, H., & Ali, R. R. (2018) Catalytic upgrading of sugarcane bagasse pyrolysis vapours over rare earth metal (Ce) loaded HZSM-5: Effect of catalyst to biomass ratio on the organic compounds in pyrolysis oil. *Applied Energy* (220) 787–799.

Balat, M. (2008). Mechanisms of thermochemical biomass conversion processes. Part 3: reactions of liquefaction. *Energy Source Part A* 30 (7) 649 - 659.

Barton, R. R., Carrier, M., Segura, C., Fierro, J. L. G., Escalona, W., Reretti, S. W. (2017) Ni/HZSM-5 catalyst preparation by deposition precipitation. Part 1. Effect of nickel loading and preparation conditions on catalyst properties. *Applied Catalysis A: General* (540) 7 – 20.

Barton, R. R., Carrier, M., Segura, C., Fierro, J. L. G., Park, S., Lamb, H. H., Peretti, S. W. (2018) Ni/HZSM-5 catalyst preparation by deposition-precipitation. Part 2. Catalytic hydrodeoxygenation reactions of lignin model compounds in organic and aqueous systems. *Applied Catalysis A: General* (562) 294–309.

Beck, J.S., Vartuli, J.C., Roth, W.J., Leonowicz, M.E., Kresge, C.T., Schmitt, K.D. (1992). A new family of mesoporous molecularsieves prepared with liquid-crystal templates. *Journal of American Chemistry Society.* (27) 10834 - 10843.

Berkgaut, V., Singer, A. (1996). High capacity cation exchanger by hydrothermal zeolitization of coal fly ash, *Science* .369–378.

Bhoi, P. R., Ouedraogo, A. S., Soloiu, V., Quirino, R. (2020) Recent advances on catalysts for improving hydrocarbon compounds in bio-oil of biomass catalytic pyrolysis. *Renewable and Sustainable Energy Reviews* (121) 109676.

Biller, P., Madsen, R. B., Klemmer, M. (2016). Effect of hydrothermal liquefaction aqueous phase recycling on biocrude yields and composition. *Bioresource Technology* (102) 190 -199.

Bohre, A., Hočevar, B., Grilc, M., Likozar, B. (2019) Selective catalytic decarboxylation of biomass derived carboxylic acids to bio-based methacrylic acid over hexaaluminate catalysts. *Applied Catalysis B: Environmental* (256) 117889.

Bridgwater, A. V. (2012). Review of fast pyrolysis of biomass and product upgrading. *Biomass Bioenergy.* (38) 68–94.

Bridgwater, A.V. (2003) Renewable fuels and chemicals by thermal processing of biomass. *Chemical Engineering Journal* (91) 87–102.

Brunner, G. (2009) Near critical and supercritical water. Part 1. Hydrolytic ans hydrothermal processes. *Journal of Supercritical Fluids* (18 (2009) 373 – 381.

Brunner, G. Hydrothermal and supercritical water processes. First ed. Elsevier; 2014.

Bruun, N., Demesa, A. G., Tesfaye, F., Hemming, J., Hupa, L. (2019) Factors affecting the corrosive behavior of used cooking oils and a non-edible fish oil that are in contact with ferrous metals. *Energies* (24) 4812.

Bu, L., Nimlos, M. R., Robichaud, D. J., Kim, S. (2018). Diffusion of aromatic hydrocarbons in hierarchical mesoporous HZSM-5 zeolite. *Catalysis Today* (312) 73-81.

Bulushev, D. A., Ross, J. R. (2011). Catalysis for conversion of biomass to fuels via pyrolysis and gasification: a review. *Catalysis Today.* (171) 1 – 13.

Caps, V and Tsang, S. C. (2003) Heterogenisation of Os species on MCM-41. Structure of epoxidation of trans-stilbene. *Applied Catalysis A: General* (248) 19 -31.

Chaiyaomporn, K., Chavalparit, O. (2010). Fuel pellets production from biodiesel waste. *Environmental Asia.* (3) 103 – 110.

Chan, Y. H., Yusup, S., Quitain, A. T. (2015) Effect of process parameters on hydrothermal liquefaction of oil palm biomass for bio-oil production and its life cycle assessment. *Energy Conversion Management* (104) 180 – 188.

Chan,Y. H., Yusup, S., Quitain, A. Q., Uemura, Y. (2014) Bio-oil production under sub-and supercritical hydrothermal liquefaction of oil palm empty fruit bunch andkernel shell, *Appied Mechanica. Materials* (625) 881–884.

Chang, S. H. (2014). An overview of empty fruit bunch from oil palm as feedstock for bio-oil production. *Biomass Bioenergy.* (62) 174 – 181.

Chang, S. H. (2018) Bio-oil derived from palm empty fruit bunches: Fast pyrolysis, liquefaction and future prospects. *Biomass Bioenergy* (119) 263 – 276.

Chen, H., Cheng, F., Zhou, K., Chen, K., Qiao, X., Lu, P., Ouyang, J. (2018) Catalytic fast pyrolysis of rice straw to aromatic compounds over hierarchical HZSM-5 produced by alkali treatment and metal-modification, *Journal Analytical Applied Pyrolysis.* (131) 76–84.

Chen, L. –H., Li, X. –Y., Rooke, J. C., Zhang, Y. –H., Yang, X. –Y., Tang, Y., Xiao, F. –S., Su, B. –L. (2012). Hierarchically structured zeolites: synthesis, mass transport properties and applications. *Journal of Materials Chemistry.* (34) 17381 – 17403.

Chen, W-H., Lin, Y-Y., Liu, H-C., Chen, T-C., Hung, C-H., Chen, C-H. (2019). A comprehensive analysis of food waste derived liquefaction bio-oil properties for industrial application. *Applied Energy* (237) 283 – 291.

Chen, X., Huang, L., Li, Q. (1997). Hydrothermal Transformation and Characterization of Porous Silica Templated by Surfactants. *The Journal of Physical Chemistry B* (42) 8460–8467.

Chen, Y., Mu, R., Yang, M., Fang, L., Wu, Y., Wu, K., Liu, Y., Gong, J. (2017). Catalytic hydrothermal liquefaction for bio-oil production over CNTs supported metal catalysts. *Chemical Engineering Science.* (161) 299–307.

Cheng, L., Ye, X. P., He, R., Liu, S. (2009) Investigation of rapid conversion of switchgrass in subcritical water. *Fuel Processing Technology* (90) 301 – 311.

Cheng, S., Wei, L., Alsowij, M. (2017). Catalytic hydrothermal liquefaction (HTL) of biomass for biocrude production using Ni/HZSM5 catalysts. AIMS *Environmental Science.* (3) 417 – 430.

Cheng, S., Wei, L., Julson, J., Kharel, P. R., Cao, Y., Gu, Z. (2017a) Catalytic liquefaction of pine sawdust for bio-fuel development of bifunctional Zn/HZSM-5 catalyst in supercritical ethanol. *Journal of Analytical Applied Pyrolysis* (126) 257 – 266.

Cheng, S., Wei, L., Rabnawaz, M. (2018) Catalytic liquefaction of pine sawdust and in-situ hydrogenation of bio-crude over bifunctional Co-Zn/HZSM-5 catalysts. *Fuel* (223) 252 – 260.

Cheng, S., Wei, L., Zhao, X., Julson, J. (2016). Application, deactivation, and regeneration of heterogeneous catalysts in bio-oil upgrading. *Catalysts.* (6) 195.

Cheng, S., Wei, L., Zhao, X., Kadis, E., Julson, J. (2016) Conversion of prairie cordgrass to hydrocarbon biofuel over Co-Mo/HZSM-5 using a two-stage reactor system. *Energy Technology* (4) 706 – 713.

Chew, T.L., Bhatia, S. (2008) Catalytic processes towards the production of biofuels in a palm oil and oil palm biomass-based biorefinery. *Bioresource Technology* (17) 7911 – 7922.

Cho, H. S., Ryoo, R. (2012) Synthesis of ordered mesoporous MFI zeolite using carbon templates. *Microporous and Mesoporous Materials* (151) 107 – 112.

Cordeiro, N., Belgacem, M. N., Torres, I. C., Mourad, J.C. P. V.(2004). Chemical composition and pulping of banana pseudo- stems, *Industrial Crops Production* 19(2), 147–154.

Czernik, S., Bridgwater, A. V. (2004). Overview of applications of biomass fast pyrolysis oil. *Energy Fuels* (18) 590.

Dalimin, M. N.(1995) Renewable energy update: Malaysia. *Renewable Energy* (6) 435 – 439.

Dashtban, M., Schraft, H., Syed, T. A, Qin, W. (2010). Fungal biodegradation and enzymatic modification of lignin. *International Journal Biochemistry Molecules Biology.*1 (1) 36 – 50.

Daud, W. R. W., Law, K. N. (2010). Oil palm fibers as paper making material: Potentials and challenges.*Bioresource* 901–917.

Demirbas, A. (2001). Biomass resource facilities and biomass conversion processing for fuels and chemicals. *Energy Conversion Management* (42) 1357–1378.

Demirbas, A. (2004). Combustion characteristics of different biomass fuels. *Process Energy Combustion.* (30) 219 – 230.

Dickerson, T and Soria, J. (2013) Catalytic fast pyrolysis: a review. *Energies* (1) 514 – 538.

Diez, A. S., Alvarez, M., & Volpe, M. A. (2015). Metal-Modified Mesoporous Silicate (MCM-41) Material: Preparation, Characterization and Applications as an Adsorbent. *Journal of the Brazilian Chemical Society.*

Dimitriadis, A., & Bezergianni, S. (2017). Hydrothermal liquefaction of various biomass and waste feedstocks for biocrude production: A state of the art review. *Renewable and Sustainable Energy Reviews* (68) 113 – 125.

Ding, K., Zhong, Z., Wang, J., Zhang, B., Addy, M., & Ruan, R. (2017). Effects of alkali-treated hierarchical HZSM-5 zeolites on the production of aromatic hydrocarbons from catalytic fast pyrolysis of waste cardboard. *Journal of Analytical and Applied Pyrolysis* (125) 153–161.

Ding, Y. J., Zhao, C. X., Liu, Z-C. (2019) Catalytic hydrothermal liquefaction of rice straw for production of monomers phenol over metal supported mesoporous catalyst. *Bioresource Technology* (294) 12209 - 12220.

Duan, P., & Savage, P. E. (2011). Hydrothermal Liquefaction of a Microalga with Heterogeneous Catalysts. *Industrial & Engineering Chemistry Research* (1) 52 – 61.

Duan, P., Xu, Y., Wang, F., Wang, B., Yan, W. (2016). Catalytic upgrading of pretreated algal biooil over zeolite catalysts in supercritical water. *Biochemistry Engineering Journal.(*116) 105–12.

Dündar-Tekkaya, E and Yürüm, Y. (2016). Mesoporous MCM-41 material for hydrogen storage: a short review. *International Journal of Hydrogen Energy.* (101) 1- 7.

Durak, H., Aysu, T. (2014). Effects of catalysts and solvents on liquefaction of *Onopordum heteracanthum* for production of bio-oils. *Bioresource Technology.* (166) 309 – 317.

EIA, U.S. (2010) *Intenrational Energy Outlook*. www.eia.gov/oiaf/ieo/index.html DOE/EIA-0484(2010)

Ergün, A.N., Kocabas, Z.O., Baysal, M., Yurüm, A., Yurüm, Y. (2013). Synthesis of mesoporous MCM-41 materials with low-power microwave heating. *Chemical Engineering Communications* (8) 1057 - 1070.

Fan, S. –P., Zakaria, S., Chia, C. –H., Jamaluddin, F., Nabihah, T., Liew, -K. (2011). Comparative studies of products obtained from solvolysis liquefaction of oil palm empty fruit bunch fibres using different solvents. *Bioresource Technology* (102) 3521 – 3526.

Feng, J., Hse, C., Yang, Z., Wang, K., Jiang, J., & Xu, J. (2017). Liquid phase in situ hydrodeoxygenation of biomass-derived phenolic compounds to hydrocarbons over bifunctional catalysts. *Applied Catalysis A: General* (542) 163–173.

Galadima, A., Muraza, O. (2018). Hydrothermal liquefaction of algae and bio-oil upgrading into liquid fuels: role of heterogeneous catalysts. *Renewable Sustainable Reviews. (*81) 1037 – 1048

Garcia-Perez, M., Chaala, A., Parkdel, H., Kretschmer,D, Roy, C. (2007). Characterization of bio-oils in chemical families. *Biomass Bioenergy* (31) 222 -242.

Garcia-Perez, M., Wang, X. S., Shen, J., Rhodes, M. J., Tian, F., Lee, W. J., Wu, H. W., Li, C. Z. (2008) Fast pyrolysis of oil mallee woody biomass: effect of temperature on the yield and quality of pyrolysis products. *Industrial Engineering Chemistry Research* (47) 1846 - 1854.

Garrote, G., Dominguez, H., Parajo, J. (1999). Hydrothermal processing of lignocellulosic materials. *Europe Journal of Wood Production* (57) 191–202.

Gollakota, A. R. K., Kishore, N., Gu, S. (2018). A review on hydrothermal liquefaction of biomass, *Renewable Sustainable Energy Reviews.* (81) 1378–1392.

Govindasamy, G., Sharma, R., Subramaniam, S. (2019). Studies on the effect of heterogenous catalysts on the hydrothermal liquefaction of sugarcane bagasse to low-oxygen containing bio oil. *Biofuels.* 224 - 231.

Grilc, M., Likozar, B., Levec, J. (2015b) Kinetic model homogeneous lignocellulosic biomass solvolysis in glycerol and imidazolium-based ionic liquids with subsequent heterogeneous hydrodeoxygenation over $NiMo/Al_2O_3$ catalyst. *Catalysis Today* (256) 302 -314.

Grilc, M., Likozar, B., Levec, J. (2016) Simultaneous liquefaction and hydrodeoxygenation of lignocellulosic biomass over $NiMo/Al_2O_3$, Pd/Al_2O_3 and zeolite Y catalysts in hydrogen donor solvents. *ChemCatChem.* 8 180 – 191.

Grilc, M.., Veryasov, G., Likozar, B., Jesih, A., Levec, J. (2015a) Hydrodeoxygenation of solvolysed lignocellulosic biomass by unsupported MoS_2, MoO_2, Mo_2C and WS_2 catalysts. *Applied Catalysis B: Environmental* (163) 467 – 477.

Guo, F., Guo, S. Q., Wei, X. X., Wang, X. Z., Xiang, H. W., Qiu, Zhao, L. F. (2014). MCM-41 upports modified by Al, Zr and Ti for NiW hydrodenitrogenation catalysts, *Cataysis. Letter* (144) 1584-1593.

Guo, Y., Wang, S. Z., Xu, D. H., Gong, Y. M., Ma, H. H., Tang, X. Y. (2010). Review of catalytic supercritical water gasification for hydrogen production from biomass. *Renewable Sustainable Energy Reviews* (14) 334 – 343.

Gupta, K. K., Rehman, A., Sarviya, R.M. (2010). Bio-fuels for the gas turbine: a review. *Renewable Sustainable Energy Review.*14 (9) 2946 - 2955.

Hahn-Hägerdal B., Galbe M., Gorwa-Grauslund M.-F., Lidén G., Zacchi G. (2006). Bio-ethanol–the fuel of tomorrow from the residues of today. *Trends in Biotechnology* (24) 549–556.

Hara, M., Nakajima, K., Kamata, K. (2015). Recent progress in the development os solid catalysts for biomass conversion into high value-

added chemicals. *Science and Technology of Advanced Materials.* 16 (3) 1-22.

Hartmann, M., Machoke, A.G., Schwieger, W. (2016) Catalytic test reactions for the evaluation of hierarchical zeolites. *Chemistry Society Reviews* (45) 3313 – 3330.

Hasan, F., Singh, R., Li, G., Zhao, D., Webley, P. A. (2012). Direct synthesis of hierarchical zeolite via a low crystallization and growth rate technique in presence of cetyltrimethylammonium bromide. *Journal of Colloid and Interface Science* (382) 1 – 12.

Hassan, A., Salema, A. A., Ani, F. N., Abu Bakar, A. (2010). A review on oil palm empty fruit bunch fiber-reinforced polymer composite materials. *Polymer Composition.* 31 (12) 2079 - 3101.

He, T., Wang, Y., Miao, P., Li, J., Wu, J., Fang, Y. (2013). Hydrogenation of naphthalene over noble metal supported on mesoporous zeolite in the absence and presence of sulfur. *Fuel.* (106) 365 – 371.

Higman, C., Vander Burgt, M. (2011) Gasification. 2nd ed Gulf professional publishing.

Higo, T., Saito, H., Ogo, S., Sugiura, Y., Sekine, Y. (2017) Promotive effect of Ba addition on the catalytic performance of Ni/LaAlO 3 catalysts for steam reforming of toluene. *Applied Catalysis A: General* (53) 125–131.

Holm, M. S., Taarning, E, Egeblad, K., Christensen, C. H. (2011). Catalysis with hierarchical zeolites, *Catalysis Today* (168) 3–16.

Hossain, A. K., Davies, P. A. (2013). Pyrolysis liquids and gases as alternative fuels in internal combustion engines: a review. *Renewable Sustainable Energy Review.* 21 (0) 165 - 189.

http://bepi.mpob.gov.my/index.php/en/production/production-2019/production-of-crude-oil-palm-2019.html

http://bepi.mpob.gov.my/index.php/en/sectoral-status/sectoral-status-2017/number-a-capacities-of-palm-oil-sectors-2017.html

http://mpoc.org.my/monthly-palm-oil-trade-statistics-2019/

https://www.fas.usda.gov/data/world-agricultural-production

Huang, H. J., Yuan, X. Z. (2015). Recent progress in the direct liquefaction of typical biomass. *Energy Combustion Science.* (49) 59-80.

Huang, W., Gong, F., Fan, M., Zhai, Q., Hong, C., Li, Q. (2012) Production of light olefins by catalytic conversion of lignocellulosic biomass with HZSM-5 zeolite impregnated with 6wt.% lanthanum. *Bioresource Technology* (121) 248–255.

Huynh, T.M., Armbruster, U., Pohl, M.M., Schneider, M., Radnik, J., Hoang, D.L. (2014) Hydrodeoxygenation of phenol as a model compound for bio-oil on non-noble bimetallic nickel-based catalysts. *ChemCatChem* (6) 1940 – 1951.

Ibarra-Gonzalez, P., Rong, B. –G. (2018). A review of the current state of biofuels production from lignocellulosic biomass using thermochemical routes. *China Journal Chemistry (5) 211 – 220.*

Ibrahim, S. M., ,Badri, K. H., Hassan, O. (2012). A study on glycerolysis of oil palm empty fruit bunch fiber. *Sains Malaysiana* (41) 1579 – 1585.

Idris, S. S., Rahman, N. A., Ismail, K., Alias, A. B., Rashid, Z. A., Aris, M. J. (2010). Investigationon thermochemical behavior of low rank Malaysian coal, oil palm biomass and their blends during pyrolysis via thermogravimetric analysis (TGA). *Bioresource Technology.* (101) 4584 – 4592.

Idris, S.A., Davidson, C.M., McManamon, C., Morris, M.A., Anderson, P., Gibson, L.T. (2011) Large pore diameter MCM-41 and its application for lead removal from aqueous media. *Journal of Hazard Materials* (185) 898 - 904.

IEA *World Energy Outlook 2010.* International Energy Agency, 2010.

Iliopoulou, E. F., Stefanidis, S., Kalogiannis, K., Delimitis, A., Lappas, A., Triantafyllidis, K. (2012) Catalytic upgrading of biomass pyrolysis vapors using transition metal-modified ZSM-5 zeolite. *Applied Catalysis B: Environmental* (127) 281 – 290.

Iliopoulou, E.F., Stefanidis, S., Kalogiannis, K., Psarras, A.C., Delimitis, A., Triantafyllidis, K.S., Lappas, A.A. (2014) Pilot-scale validation of Co-ZSM-5 catalyst performance in the catalytic upgrading of biomass pyrolysis vapours. *Green Chemistry* (16) 662 – 674.

Iliopoulou, E.F., Triantafyllidis, K.S., Lappas, A.A. (2018) Overview of catalytic upgrading of biomass pyrolysis vapors toward the production of fuels and high-value chemicals. Wiley Interdiscipline *Reviews Energy Environmental* (8) 322.

Isahak, W. N. R. W., Hisham, M. W. M., Yarmo, M.A., Taufiq-Yap, Y.H. (2012). A review on bio-oil production from biomass by using pyrolysis method. *Renewable Sustainable Energy Review.* 16 (8) 5910 – 5923

Isha, R., Williams, P. T. (2012). Experimental design methodology for optimizing catalytic performance of Ni/Ce-α-Al_2O_3 catalyst for methane steam reforming. *Journal of the Energy Institute.* (85) 22 -28.

Jacobsen, C. J. H., Madsen, C., Houzvicka, J., Schmidt, I., Carlsson, A. (2000). Mesoporous zeolite single crystals. *Journal of American Chemical Society*. (122) 7116 – 7117.

Jae, J., Tompsett, G. A., Foster, A. J., Hammond, K. D., Auerbach S. M., Lobo, R. F., Huber, G. W. (2011). Investigation into the shape selectivity of zeolite catalysts for biomass conversion, *Journal of Catalysis.* (279) 257–268.

Janssen, A. H., Koster, A. J., Jong, K. P. De. (2001). Three – dimensional transmission electron microscopic observations of mesopores in Y-dealuminated zeolite. *Angewandte Chemie* (40) 1102 – 1104.

Jiang, J., Junming, X., Zhanqian, S. (2015) Review of the direct thermochemical conversion of lignocellulosic biomass for liquid fuels. *Frontiers Agricultural Science Engineering* (2) 13 – 27.

Joffres, B., Nguyen, M. T., Laurenti, D., Lorentz, C., Souchon, V., Charon, N., Quignard, A., Geantet, C. (2016) Lignin hydroconversion on MoS2, MoO2, Mo2C and WS2 catalysts. *Applied Catalysis B: Environmental* (184) 153 – 162.

Kadkhodayan, A. and Brenner, A. (1989)Temperature-Programmed Reduction and Oxidation Supported on y-Alumina. *Journal of Catalysis.* (321) 311 – 321.

Kaewmeesri, R., Srifa, A., Itthibenchapong, V., & Faungnawakij, K. (2015). Deoxygenation of Waste Chicken Fats to Green Diesel over Ni/Al2O3: Effect of Water and Free Fatty Acid Content. *Energy & Fuels* 29 (2) 833–840.

Kantarelis, E., Yang, W., Blasiak, W. (2014) Effect of zeolite to binder ratio on product yields and composition during catalytic steam pyrolysis of biomass over transition metal modified HZSM-5. *Fuel* (122) 119 – 125.

Kawai, T., Tsutsumi, K. (1999). A study on the surface silanol groups developed by hydrothermal and acid treatment of faujasite type zeolites. *Journal of Colloid and Interface Science.* 212 (2) 310 -316.

Kerdsuwan, S., Laohalidanond, K. (2011). Renewable energy from palm oil empty fruit bunch. In: Nayeripour M, editor. Renewable energy: trends and applications. Shanghai: InTech. pp. 123 - 150.

Khajavi, S. H., Kimura, Y., Oomori, T., Matsuno, R., Adachi, S. (2005) Kinetics on sucrose decomposition in subcritical water. *Food Science Technology* (38) 397 – 302.

Khan, W., Jia, X., Wu, Z., Choi, J., Yip, A. C. K. (2019) Incorporating hierarchy into conventional zeolites for catalytic biomass conversion: a review. *Catalysts* (2) 127 – 150.

Khosbin, R., Haghighi, M. (2013). Direct syngas to DME as a clean fuel: the beneficial use of ultrasound for the preparation of CuO-ZnO-Al2O3/HZSM-5 nanocatalyst. *Journal of Catalysis.* (91) 1111 -1122.

Kim, S. W., Koo, B. S., Ryu, J. W., Lee, J.S., Kim, C. J., Lee, D. H. (2013). Bio-oil from the pyrolysis of palm and Jatropha wastes in a fluidized bed. *Fuel Processing Technology.* (108) 118 – 124.

Kresge, C.T., Leonowicz, M.E., Roth, W.J., Vartuli, J.C., Beck, J.S. (1992). Ordered mesoporous molecular-sieves synthesized by a liquid-crystal template mechanism. *Nature* (6397) 710 – 712.

Krishnan, Y., Bong, C. P. C., Azman, N. F., Zakaria, Z., Othman, N., Abdullah, N. (2017) Co-composting of palm empty fruit bunch and palm oil mill effluent: microbial diversity and potential mitigation of greenhouse gas emission. *Journal of Clean Production* (146) 94 -100.

Kruk, M. (2012) Access to ultralarge-pore ordered mesoporous materials through selection of surfactant/swelling-agent micellar templates. *Accounts of Chemical Research* (45) 1678 – 1687.

Kumar, M., Oyedun, A. O., Kumar, A. (2017). A review on the current status of various hydrothermal technologies on biomass feedstock. *Renewable Sustainable Energy Review.* Article in press

Kumar, R., Strezov, V., Kan, T., Weldekidan, H., He, J., & Jahan, S. (2020). Investigating the effect of mono and bimetallic/zeolite catalysts on hydrocarbon production during bio-oil upgrading from ex-situ pyrolysis of biomass. *Energy & Fuels.* (34) 389 – 397.

Kunieda, H., Ozawa, K., & Huang, K.-L. (1998). Effect of Oil on the Surfactant Molecular Curvatures in Liquid Crystals. *The Journal of Physical Chemistry B* (5) 831 – 838.

Lakiss, L., Ngoye, F., Canaff, C., Laforge, S., Pouilloux, Y., Qin, Z., Tarighi, M., Thomas, K., Valtchev, V., Vicente, A., Pinard, L., Gilson, J.P., Fernandez, C. (2015). On the remarkable resistance to coke formation of nanometer-sized and hierarchical MFI zeolites during ethanol to hydrocarbons transformation. *Journal of Catalysis* (328) 165-172.

Lee, C.K., Liu, S.S., Juang, L.C., Wang, C.C., Lin, K.S., Lyu, M.D. (2007) Application of MCM-41 for dyes removal from wastewater. *Journal of Hazard Materials* (3) 997 - 1005.

Lee, H., Lee, H., Ha, J. –M., Kim, J., Suh, D. J. (2015). Production of aromatic compounds from oil palm empty fruit bunches by hydro- and solvothermolysis. *Industrial Crops And Products.* (76) 104 -111.

Lee, J. (1997). Biological conversion of lignocellulosic biomass to ethanol. *Journal of Bioresource Technology* (83) 37–46.

Lee, J. H., Hwang, H., Choi, J. W. (2018). Effects of transition metals on hydrothermal liquefaction of empty fruit bunches (EFB) for conversion of biofuel and valuable chemicals. *Energy*. (162) 1-9.

Lelifajri, R. and Shabrina, J. (2017) Preparation of chitosan composite film reinforced with cellulose isolated from oil palm empty fruit bunch and application in cadmium ions removal from aqueous solutions. *Carbohydrate Polymer* (170) 226 -233.

Leng, S., Wang, X., He, X., Liu, L., Liu, Y., Zhong, X., Zhuang, G., Wang, J-g. (2013) NiFe/γ-Al_2O_3: A universal catalyst for the hydrodeoxygenation of bio-oil and its model compounds. *Catalysis Communications* (41) 34 -37.

Li, D., Bui, P., Zhao, H., Oyama, S., Dou, T., Shen, Z. (2012). Rake mechanism for the deoxygenation of ethanol over a supported Ni_2P/SiO_2 catalyst. *Journal of Catalysis* (290) 1 – 12.

Li, M., Liu, D., Wu, P. P., Cong, X. S., Song, L. H., Chen, Q. T., Liu, J., Wu, H., Yan, Z. F. (2016) Efficient hydroliquefaction of sawdust over a novel silica-supported monoclinic molybdenum dioxide catalyst. *Energy Fuels.* (30) 6495 – 6499.

Li, N. X., Wei, L. F., Bibi, R., Chen, L. Y., Liu, J. H., Zhang, L., Zheng, Y. Q., Zhou, J. C. (2016) Catalytic hydrogenation of alkali lignin into bio-oil using flower-like hierarchical MoS2-based composite catalysts. *Fuel.* (185) 532 – 540.

Li, X., Zhang, X., Shao, S., Dong, L., Zhang, J., Hu, C., Cai, Y. (2018) Catalytic upgrading of pyrolysis vapor from rape straw in a vacuum pyrolysis system over La/HZSM-5 with hierarchical structure, *Bioresource Technology* (259) 191 – 197.

Li, Y., Li, L., & Yu, J. (2017). Applications of Zeolites in Sustainable Chemistry. *Chemistry* (6) 928 – 949.

Limayem, A., Ricke, S. C. (2012) Lignocellulosic biomass for bioethanol production: current perspectives, potential issues and future prospects. *Journal of Catalysis* (4) 449 – 467

Liu, B., Zheng, L., Zhu, Z., Li, C., Xi, H., Qian, Y. (2014). Hierarchically structured Beta zeolites with intercrystal mesopores and the improved catalytic properties. *Applied Catalysis A: General.* (470) 412 – 419.

Liu, C., Kong, L., Wang, Y., Dai, L. (2018). Catalytic hydrothermal liquefaction of spirulina to bio-oil in the presence of formic acid over palladium-based catalysts. *Algal Resource* (33) 156 – 164.

Liu, T., Cao, J., Zhao, X., Wang, J., Ren, X., Fan, X., Zhao, Y., Wei, X. (2017) In situ upgrading of Shengli lignite pyrolysis vapors over metal-loaded HZSM-5 catalyst. *Fuel Process Technology* (160) 19 – 26.

Liu, Z., Zhang, F. S. (2008). Effects of various solvents on the liquefaction of biomass to produce fuels and chemical feedstocks. *Energy Conversion Management.* 49 (12) 3498 – 3504

Llinas, M.C.; Sánchez, D. Nanopartículas de sílice: Preparación y aplicaciones en biomedicina. Affinidad 2014, LXXI, 20–31

Loh, S. H. (2016). The potential of the Malaysian oil palm biomass as a renewable energy source. *Energy Conversion and Management*. (141) 285 – 298.

Long, J. X., Li, Y. W., Zhang, X., Tang, L., Song, C. H., Wang, F. R. (2016) Comparative investigation on hydrothermal and alkali catalytic liquefaction of bagasse: process efficiency and product properties. *Fuel.* (186) 685 – 693.

Loy, A. C. M., Yusup, S., Chin, B. L. F., Gan, D. K. W., Shahbaz, M., Acda, M. N., Unrean, P., Rianawati E. (2018). Comparative study of in-situ catalytic pyrolysis of rice husk for syngas production: kinetics modeling and product gas analysis. *Journal Clean Production.* (197) 1231- 1243.

Luo,S. S., Fan, G. Z., Luo, M., Li, J. F., Song, G. S. (2016) Synthesis of styrene carbonate from styrene oxide and carbon dioxide over $ZnBr_2$ supported on MCM-41 coated magnetic Fe_3O_4. *Journal of Carbon Dioxide Utilization*, (14) 23 - 30.

Ma, R., Hao, W. Y., Ma, X. L., Tian, Y, Li, Y. D. (2014) Catalytic ethanolysis of Kraft Lignin into high value small-molecular chemicals over a nanostructured α-molybdenum carbide catalyst. *Angewandte Chemie International Edition* (53) 7310 – 7315.

Malaysia Palm Oil Council (MPOC): Palm Oil & Palm Kernel Oil Application. MPOC (2006) i–v.

Mantilla, S. V., Manrique, A. M., & Gauthier-Maradei, P. (2015). Methodology for Extraction of Phenolic Compounds of Bio-oil from Agricultural Biomass Wastes. *Waste and Biomass Valorization*, 6(3), 371–383

Martinez, R., Romero, E., Garcia, L., Bilbao, R. (2003) The effect of lanthanum on Ni-Al catalyst for catalytic steam gasification of pine sawdust. *Fuel Process Technology* (85) 201 – 210.

Mathimani, T., Mallick, N. (2019). A review on the hydrothermal processing of microalgal biomass to bio-oil – knowledge gaps and recent advances. *Journal Clean Production.* (217) 69–84.

McKendry, P. (2002) Energy production from biomass (part2): conversion technologies. *Bioresource Technology* (83) 47–54.

Meng, J., Moore, A., Tillota, D. C., Kelley, S. S., Adhikari, S., P. Sunkyu. (2015) Thermal and storage stability of bio-oil from pyrolysis of torrefied wood. *Energy Fuel.* (29) 5117 – 5126.

Menon, N. R., Rahman, Z., Bakar, N. (2003). Empty fruit bunches evaluation: Mulchin plantation vs. fuel for electricity generation. *Oil Palm Industrial Economy Journal.(*3) 15–20.

Meryemo_glu, B., Hasano_glu, A., Irmak, S., Erbatur, O. (2014). Biofuel production by liquefaction of kenaf (Hibiscus cannabinus L.) biomass. *Bioresource Technology.* 151 (0) 278 -283.

Misson, M., Haron, R., Kamaroddin, M. F. A., Amin, N. A. S. (2009). Pretreatment of empty palm fruit bunch for production of chemicals via catalytic pyrolysis. *Bioresource Technology* (100) 2867 – 2873.

Mochizuki, T., Chen, T-Y., Toba, M., Yoshimura, Y. (2013). Pyrolyzer-GC/MS system-based analysis of the effects of zeolite catalysts on the fast pyrolysis of Jatropha husk. *Appied Catalysis General: A* (456) 174 – 181.

Mohammad, N., Alam, M. Z., Kabbashi, N.A., Ahsan, A. (2012). Effective composting of oil palm industrial waste by filamentous fungi: a review. *Resource Conservation Recycle*. 58 (0) 69 - 78.

Mortensen, P. M., Grunwaldt, J. D., Jensen, P. A., Knudsen, K. G., Jensen, A. D. (2011) A review of catalytic upgrading of bio-oil to engine fuels. *Applied Catalysis A- General* 407 1-19.

Mortensen, P. M., Grunwaldt, J. D., Jensen, P. A., Knudsen, K. G., Jensen, A. D. (2011) A review of catalytic upgrading of bio-oil to engine fuels. *Applied Catalysis A- General* 407 1-19

Naik, S. N., Goud, V. V., Rout, P. K., Dalai, A. K. (2010) *Renewable Sustain. Energy Rev*. (14) 578–597.

Nishu, R., Liu, Md., Rahman, M. M., Sarker, M., Chai, M., Li, C., & Cai, J. (2020). A review on the catalytic pyrolysis of biomass for the bio-oil production with ZSM-5: Focus on structure. *Fuel Processing Technology*, (199) 106301.

Oasmaa, A., Czernik, S. (1999). Fuel oil quality of biomass pyrolysis oils: State of the art for the end users. *Energy Fuels* (13) 914.

Oemar. U., Ang, M. L., Hidajat, K., Kawi, S. (2015) Enhancing performance of Ni/La_2O_3 catalyst by Sr – modification for steam reforming of toluene as model compound of biomass tar. *Royal Society Chemistry Advances* (23) 17834 – 17842.

Okuda, K., Umetsu, M., Takami, S., Adschiri, T. (2004) Disassembly of lignin and chemical recovery - rapid depolymerization of lignin without char formation in water – phenol mixtures. *Fuel Process Technology* (85) 803 – 813.

Onyanga, D.O., Kaluli, J. W. Pyrolysis: An alternative technology for municipal solid waste management. Proceeding of the 2013 JKUAT Scientific Technological and Industrialization Conference, 14 – 15th November, pp. 948 – 959 Nairobi, Kenya.

Panda, A. K., Singh, R., Mishra, D. (2010) Thermolysis of waste plastics to liquid fuel: a suitable method for plastic waste management and

manufacture of value added products – a world prospective. *Renewable Sustainable Energy Reviews* (14) 233 - 248.

Pang, S. (2019). Advances in thermochemical conversion of woody biomass to energy, fuels and chemicals. *Biotechnology Advance.* 589-597.

Park, H. J., Heo, H. S., Jeon, J. K., Kim, J., Ryoo, R., Jeong, K. –E., Park, Y. – K. (2010) Highly valuable chemicals production from catalytic upgrading of radiate pine sawdust-derived pyrolytic vapors over mesoporous MFI zeolites. *Applied Catalysis: B* (3) 365 -373.

Pattiya, A., Titiloye, J. O., Bridgwater, A. V. (2008) Fast pyrolysis of cassava rhizome in the presence of catalysts. *Journal of Analytical Applied Pyrolysis* (81) 72 – 79.

Peng, B., Yao, Y., Zhao, C., Lercher, J. A. (2012). Towards quantitative conversion of microalgae oil to diesel-range alkanes with bifunctional catalysts. *Angewandte Chemie.* (9) 2072 – 2075.

Peng, J., Chen, P., Lou, H., Zheng, X. (2009) Catalytic upgrading of bio-oil by HZSM5 in sub- and super-critical ethanol. *Bioresource Technology* (100) 3415 – 3418.

Perego, C., Bianchi, D. (2010). Biomass upgrading through acid/base catalysis, *Chemica. Engineering Journal* 161 (3) 314–322.

Prasertsan, S., Prasertsan, P. (1996). Biomass residues from palm oil mills inThailand: An overview on quantity and potential usage. *Biomass Bioenergy* (11) 387 – 395.

Pua, F. L., Zakaria, S., Chia, C. H., Fan, S. P., Rosenau, T., Potthast, A., Liebner, F. (2013). Solvolytic liquefaction of oil palm empty fruit bunch (EFB) fibres: analysis of product fractions using FTIR and pyrolysis-GCMS, *Sains Malaysiana* (42) 793–799.

Rachel–Tang, D. Y., Islam, A., Taufiq-Yap, Y. H. (2017). Bio-oil production via catalytic solvolysis of biomass. *Royal Society of Chemistry Advances.* (7) 7820 – 7830.

Rafidah, J., Asma, W., Puad, E., Mahanim, S. M. A., Shaharuddin, H. Toward zero waste production of value added products from waste oil palm trunk (WOPT). In: Proceeding of 8th Biomass Asia Workshop; 2 – 3 July, Hanoi-Vietnam. 2012, 25 – 46.

Ragauskas, A. J., Williams, C. K., Davison, B. H., Britovsek, G., Cairney, J., Eckert, C. A., Frederick, W. J., Hallett, J. P., Leak, D. J., Liotta, C. L., Mielenz, J. R., Murphy, R., Templer, R., Tschaplinski, T. (2006), The path forward for biofuels and biomaterials. *Science.* 311 (5760), 484−489

Ramirez, J. A., brown, R. J., Rainey, T. J. (2015) A review of hydrothermal liquefaction bio-crude properties and prospects for upgrading to transportation fuels. *Energies* (8) 6765 – 6794.

Rana, M.S., Srinivas, B. N., Maity, S. K., Dhar, G. M., Rao, T. S. R. P. (2000) Origin of cracking functionality of sulfide (Ni) $CoMo/SiO_2$-ZrO_2 catalysts. *Journal of Catalysis* (195) 31 – 37.

Reding, G., Maurer, T., Kaushaan, B. (2003) Comparing synthesis routes to nano-crystalline zeolite ZSM-5. *Microporous and Mesoporous Materials* (57) 83 – 92.

Rezaei, P. S., Shafaghat, H., Daud, W. M. A. W. (2014). Production of green aromatics and olefins by catalytic cracking of oxygenate compounds derived from biomass pyrolysis: a review. *Appied Catalysis General: A* (469) 490 – 511.

Rubin, E. M. (2008). Genomics of cellulosic biofuels. *Nature*. 454 (7206) 841 – 845.

Saber, M., Golzary, A., Hosseinpour, M., Takahashi, F., & Yoshikawa, K. (2016). Catalytic hydrothermal liquefaction of microalgae using nanocatalyst. *Applied Energy* (183) 566–576.

Saidur, R., Abdelaziz, E. A., Demirbas, A., Hossain, M.S., Mekhilef, S. (2011). A review on biomass as a fuel for boilers. *Renewable Sustainable Energy Review.* 15 (5) 2262 - 2289.

Saini, J. K., Saini, R., & Tewari, L. (2014). Lignocellulosic agriculture wastes as biomass feedstocks for second-generation bioethanol production: concepts and recent developments. *Biotechnology* 5(4), 337–353.

Sanna, A., Vispute, T. P., Huber, G. W. (2015) Hydrodeoxygenation of the aqueous fraction of bio-oil with Ru/C and Pt/C catalysts. *Applied Catalysis B: Environmental* (165) 446 – 456.

Sekine, Y., Higo, T., Saito, H., Sugiura, Y., Ogo, S. (2017) Promotive effect of Ba addition on the catalytic performance of Ni/LaAlO 3 catalysts for steam reforming of toluene. *Applied Catalysis A* (530) 125 – 131.

Serapiglia, M.J., Mullen, C.A., Lawrence, B.S., Boateng, A.A. (2015) Variability in pyrolysis product yield from novel shrub willow genotypes. *Biomass Bioenergy* (72) 74 – 84.

Serrano, D. P., Escola, J. M., Pizarro, P. (2013) Synthesis strategies in the search for hierarchical zeolites. *Chemistry Society Reviews* (42) 4004 – 4035.

Serrano, D.P., Sanz, R., Pizarro, P., Peral, A., Moreno, I. (2013). Improvement of the hierarchical TS-1 properties by silanization of protozeolitic units in presence of alcohols. *Microporous and Mesoporous Materials*. (166) 59 – 66.

Sharma, R., Tiwari, A. K., Singh, A., & Sharma, N. (2019). Catalytic Hydrothermal Liquefaction of Microalgae using Fe-MCM 41 Catalyst in Presence of Carbon Monoxide. *Asian Journal of Chemistry* (3) 690 – 694.

Shi, N., Liu, Q-y., Jiang, T., Wang, T-j., Ma, L-l., Zhang, Q., Zhang, H-h. (2012) Hydrodeoxygenation of vegetable oils to liquid alkane fuels over Ni/HZSM-5 catalysts. Methyl hexadecanoate as the model compound. *Catalysis Communications* (20) 80 – 84.

Short, D. Z., Vu, D., Durbin, T. D., Karavalakis, G., Asa-Awuku, A. (2015). Components of particle emission from light – duty spark –ignition vehicles with varying aromatic content and octane rating in gasoline. *Environmental Science Technology.* (49) 10682 – 10691.

Shuai, L. and Pan, X. J. (2010) Biohydrocarbons: next generation liquid fuels from lignocellulosic biomass. *Research Progress In Paper Industry And Biorefinery* (4th Isetpp), (3) 1293 1297.

Shuit, S. H., Tan, K. T., Lee, K. T., Kamaruddin, A. H. (2009). Oil palm biomass as a sustainable energy source: a Malaysian case study.*Energy (*34) 1225 – 1235.

Shun, T., Zhang, Z., Jianping, S., Qingwen. W. (2013). Recent progress of catalytic pyrolysis of biomass HZSM-5. *Chinese Journal of Catalysis* (34) 641 – 650.

Sierra, R.. Producing Fuels and Chemicals from Lignocellulosic Biomass. (2008) *Chemical Engineering Progress*. SBE Special Section - Biofuels: p. 10 - 18.

Siew, K. W., Lee, H. C., Gimbun, J., & Cheng, C. K. (2014). Characterization of La-promoted Ni/Al2O3 catalysts for hydrogen production from glycerol dry reforming. *Journal of Energy Chemistry* 23 (1) 15–21.

Sluiter, A., Hames, B., Ruiz, C., Scarlata, C., Sluiter, J., Templeton, D., Crocken, D. (2018) Determination of structural carbohydrates and lignin in biomass. Laboratory analytical procedure (LAP). *National Renewable Energy Laboratory* 1- 18.

Somerville, S., Youngs, H., Taylor, C., Davis, S. C., Long, S. P. (2010). Feedstocks for lignocellulosic biofuels. *Science*. 329 (5993) 790–791.

Song, G., Chen, W., Dang, P., Yang, S., Zhang, Y., Wang, Y., Xiao, R., Ma, R., Li, F. (2018) Synthesis and characterization of hierarchical ZSM-5 zeolites with outstanding mesoporosity and excellent catalytic properties, *Nanoscale Research Letter.* (13)364.

Song, Q., Wang, F., Cai, J. Y., Wang, Y. H., Zhang, J. J., Yu, W. Q., Xu, J. (2013)Lignin depolymerization (LDP) in alcohol over nickel-based catalysts via fragmentation-hydrogenolysis process. *Energy Environmental Science* (6) 994 – 1007.

Srifa, A., Faungnawakji, K., Itthibenchapong, V., Assabumrungat, S. (2015). Roles of monometallic catalysts in hydrodeoxygenation of palm oil to green diesel. *Chemical Engineering Journa.* (278) 249- 258.

Sriningsih, W., Saerodji, M. G., Trisunaryanti, W., Armunanto, R., Falah, I. I. (2014). Fuel production from LDPE plastic waste over natural zeolite supported Ni, Ni-Mo, Co and Co-Mo metals. *Procedia Environmental Sciences* (20) 215 – 224.

Sugano, M., Takagi, H., Hirano, K., Mashimo, K. (2008). Hydrothermal liquefaction of plantation biomass with two kinds of wastewater from paper industry. *Journal Material Science.(*43) 2476 – 2486.

Sulaiman, F., Abdullah, N., Gerhauser, H., Shariff, A. (2011). An outlook of Malaysian energy, oil palm industry and its utilization of wastes as useful resources. *Biomass Bioenergy*. 35 (9) 3775 - 3786.

Sun, L., Guo, X., Xiong, G., Wang, X. (2012). Ethylation of coking benzene with ethanol over nano-sized ZSM-5 zeolites: effects of rare earth oxides on catalyst stability. *Catalysis Communication*. (25) 18 – 21.

Sun, P., Heng, M., Sun, S., Chen. (2010). Direct liquefaction of paulownia in hot compressed water: influence of catalysts, *Energy* (35) 5421–5429.

Taarning, E., Osmundsen, C. M., Yang, X. B., Voss, S. I., Christensen, C. H. (2011) Zeolite-catalyzed biomass conversion to fuels and chemicals. *Energy Environ. Sci*. 4 (3) 793–804.

Tang, B., Dai, W., Sun, X., Wu, G., Guan, N., Hunger, M., & Li, L. (2015). Mesoporous Zr-Beta zeolites prepared by a post-synthetic strategy as a robust Lewis acid catalyst for the ring-opening aminolysis of epoxides. *Green Chemistry.* (3) 1744–1755.

Tang, M., Xu, L., & Fan, M. (2014). Effect of Ce on 5 wt% Ni/ZSM-5 catalysts in the CO 2 reforming of CH 4 reaction. *International Journal of Hydrogen Energy* (28) 15482 –15496.

Tarka, A., Patkowski, W., Zybert, M., Ronduda, H., Wieciński, P., Adamski, P., Raróg-Pilecka, W. (2020). Synergistic Interaction of Cerium and Barium-New Insight into the Promotion Effect in Cobalt Systems for Ammonia Synthesis. *Catalysts* (6) 658 - 669.

Thangalazhy-Gopakumar, S., Adhikari, S., Gupta, R.B. (2012) Catalytic pyrolysis of biomass over H+ ZSM-5 under hydrogen pressure. *Energy Fuels* (26) 5300 – 5306.

Toor, S. S., Rosendahl, L., Rudolf, A. (2011). Hydrothermal liquefaction of biomass: a review of subcritical water technologies. *Energy* (36) 2328 – 2342.

Ulagappan, N., Rao, C. N. R. (1996). Evidence for supramolecular organization of alkane and surfactant molecules in the process of forming mesoporous silica. *Chemical Communications* (24) 2759.

Vardon, D. R., Sharma, B. K., Blazina, G. V., Rajagopalan, K., Strathmann, T. J. (2012). Thermochemical conversion of raw and defatted algal biomass via hydrothermal liquefaction and slow pyrolysis. *Bioresource Technology.* (109) 178 – 187.

Vecino, S., Mantilla, P., Gauthier-Maradei, P., Álvarez Gil., S. Tarazona Cárdenas. (2014). Comparative study of bio-oil production from sugarcane bagasse and palm empty fruit bunch: yield optimization and bio-oil characterization, *Journal Analysis Applied Pyrolysis.* (108) 284-294.

Vekes, B., Norazana, I., Rafiziana, M. D., Ruzinah, I., Mohd Kamaruddin, A.H., Hasinah, H., Roshafira, R. A. (2018). Catalytic upgrading of sugarcane bagasse pyrolysis vapours over rare earth metal (Ce) loaded HZSM-5: effect of catalyst to biomass ratio on the organic compounda in pyrolysis oil. *Applied Energy* (220) 787 – 799.

Vekes, B., Norazana, I., Rafiziana, M. K., Ruzinah, F., Mohd. Kamaruddin, A. H., Hasrinah, H. (2020). Catalytic upgrading of biomass derived pyrolysis vapour over metal modified HZSM-5 into BTX: a comprehensive review*. Biomass Conversion and Biorefinery.* 1 - 28

Veses, A., Puértolas, B., Calléen, M., García, T. (2015). Catalytic upgrading of biomass derived pyrolysis vapors over metal-loaded ZSM-5 zeolites: effect of different metal cations on the bio-oil final properties. *Microporous Mesoporous Material.* (209) 189 – 196.

Veses, A., Puértolas, B., López, J. M., Callén, M. S., Solsona, B., Garcia, T. (2016) Promoting deoxygenation of bio-oil by metal-loaded hierarchical ZSM-5 zeolites. *ACS Sustainable Chemical Engineering* (4) 1653 – 1660.

Vichaphund, S., Aht-ong, D., Sricharoenchaikul, V., Atong, D. (2015) Production of aromatic compounds from catalytic fast pyrolysis of Jatropha residues using metal/HZSM-5 prepared by ion-exchange and impregnation methods. *Renewable Energy* (79) 28 – 37.

Vuong, G. T., Hoang, V. T., Nguyen, O. T., Do, T. O. (2010) Synthesis of nanozeolites and nanozeolite-based FCC catalysts and their catalytic activity in gas oil cracking reaction. *Applied Catalysis A: General* (382) 231 – 239.

Wang, K., Kim, K. H., Brown, R. C. (2014) Catalytic pyrolysis of individual components of lignocellulosic biomass. *Green Chemistry* (2) 727 – 735.

Wang, L., Lei, H., Bu, Q., Ren, S., Wei, Y., Zhu, L. (2014) Aromatic hydrocarbons production from ex situ catalysis of pyrolysis vapor over

Zinc modified ZSM-5 in a packed-bed catalysis coupled with microwave pyrolysis reactor. *Fuel* (129) 78 – 85.

Wang, W., Xu, Y., Wang, X., Zhang, B., Tian, W., Zhang, J. (2018). Hydrothermal liquefaction of microalgae over transition metal supported TiO2 catalyst. *Bioresource Technology. (*250) 474 – 480.

Wang, Y. and Wang, S. (2013). Hierarchical zeolites: Synthesis and applications in bioenergy. *Open Journal of Advanced Materials Research*. (2) 13 – 23.

Wang, Y. Wang, S. (2016) Hierarchical zeolites: Synthesis and applications in Bioenergy. *Open journal Advanced Materials Research* 1(2), 13-23.

Wang, Y. Y., Ling, L. L.,Jiang, H. (2016) Selective hydrogenation of lignin to produce chemical commodities by using a bio-char supported Ni-Mo2C catalyst obtained from biomass. *Green Chemistry* (18) 4032 – 4041.

Wang, Y., Fang, Y., He, T., Hu, H., Wu, J. (2011)Hydrodeoxygenation of dibenzofuran over noble metal supported on mesoporous zeolite. *Catalysis Communication*. (12) 1201 – 1205.

Watanabe, M., Aizawa, Y., Iida, T., Aida, T. M., Levy, C., Sue, K. (2005). Glucose reactions with acid and base catalysts in hot compressed water at 473K. *Carbohydrate Resources* 1925–1930.

Weingarten, R., Conner, W. C., Huber, G. W. (2012) Production of levulinic acid from cellulose by hydrothermal decomposition combined with aques phase dehydration with solid acid catalyst. *Energy & Environmental Science* (6) 7559 – 7574.

Weitkamp, J. (2000). Zeolites and catalysis, *Solid State Ionics* (131) 175–188.

Wu. H., Zheng. J., Wang, G. (2019). Catalytic liquefaction of switchgrass in isobutanol/water system for bio-oil development over bifunctional Ni-HPMo/Fe_3O_4@AL-MCM-41. *Renewable Energy.* (141) 96 – 106.

Xinghua, Z., Tiejun, W., Longlong, M., & Chuangzhi, W. (2010). Aqueous-phase catalytic process for production of pentane from furfural over nickel-based catalysts. *Fuel* (10), 2697–2702.

Xu, J., Jiang, J., Hse, C., & Shupe, T. F. (2012). Renewable chemical feedstocks from integrated liquefaction processing of lignocellulosic materials using microwave energy*. Green Chemistry* (10) 2821 – 2829.

Xu, R.R., Pang, W. Q., Yu, J.H., Huo, Q.S., Chen, J. S. Chemistry of Zeolites abd Related Porous Materials. John Wiley & Sons, Inc., Singapore, 2007.

Xu. F., Zheng. X., Yu. H., Hu, X. (2014). Hydrothermal liquefaction of *Chlorella pyrenoidosa* for bio-oil production over Ce/HZSM-5. *Bioresource Technology.* (156) 1 – 5.

Yamamoto, Y., Nawa, N., Nishimoto. S., Kameshima, Y., Matsuda, M., Miyake, M. (2011) Temperature dependence of hydrogen adsorption properties of nickel-doped mesoporous silica. *International Journal Hydrogen Energy* (9) 5739 - 5743.

Yaman, S. (2004). Pyrolysis of biomass to produce fuels and chemical feedstocks. *Energy Conversion Management. (*45) 651–671.

Yaneva, Z., Georgieva, N., Pavlov, A. (2016). Low temperature plasma-modified zeolite vs natural Bulgarian zeolite – comparative physicochemical, spectrochemical and fourier transform infrared spectroscopy studies. *Macedonian Journal of Chemistry and Chemical Spectroscopy Studies.* (35) 97 – 105

Yang, J., Yu, S., Hu, H., Zhang, Y., Lu, J., Wang, J., Yin, D. (2011). Synthesis of ZSM5 hierarchical microsphere-like particle by two stage varying temperature crystallization without secondary template. *Chemical Engineering Journal*. (3) 1083 – 1089.

Yarulina, I., Chowdhury, A.D., Meirer, F. (2018) Recent trends and fundamental insights in the methanol-to-hydrocarbons process. *Natural Catalysis* (1) 398 – 411.

Yim, S. C., Quitain, A. T., Yusup, Sasaki, M., Uemura, Y., Kida, T. (2017). Metal oxide catalyzed hydrothermal liquefaction of Malaysian oil palm biomass to bio-oil under supercritical condition. *Journal Supercritical Fluids.* (120) 384-394.

Zhang, B., Lin, Q., Zhang, Q., Wu, K., Pu, W., Yang, M., Wu, Y. (2017) Catalytic hydrothermal liquefaction of *Euglena sp.* Microalgae over zeolite catalysts for the production of bio-oil. *Royal Society Chemistry Advances* (7) 8944 – 8951.

Zhang, H., Li, X. (2016) Novel mesoporous silica material with hierarchically ordered nanochannel: Synthesis with the assistance of straight-chain alkane and application. *Journal of Chemistry,* 11 -16.

Zhang, H., Xiao, R., Jin, B., Xiao, G., Chen, R. (2013) Biomass catalytic pyrolysis to produce olefins and aromatics with a physically mixed catalyst, *Bioresource Technology.* (140) 256–262

Zhang, J., Chen, W-T., Zhang, P., Luo, Z., Zhang, Y. (2013) Hydrothermal liquefaction of *Chlorella pyrenoidosa* in sub- and supercritical ethanol with heterogeneous catalysts. *Bioresource Technology* (133) 389 – 397.

Zhang, Q., Chang, J., Wang, T., Xu, Y. (2007). Review of biomass pyrolysis oil properties and upgrading research. *Energy Conversion Management.* (48) 87 – 92.

Zhang, Z., Wang, Y., Sun, K., Shao, Y., Zhang, L., Zhang, S.,Hu, X. (2020) Steam reforming of acetic acid over Ni-Ba/Al2O3 catalysts: Impacts of

barium addition on coking behaviors and formation of reaction intermediates. *Journal of Energy Chemistry* (43) 208 - 219

Zhao, C., Lercher, J. A. (2012) Upgrading pyrolysis oil over Ni/HZSM-5 by cascade reactions. *Angew Chem*. (126) 6037 – 6042.

Zhao, X., Wei, L., Cheng, S., Huang, Y., Yu, Y., Julson, J. (2015) Catalytic cracking of camelina oil for hydrocarbon fuel over ZSM-5-Zn catalyst. *Fuel Processing Technology* (139) 117 – 126.

Zhao, X.S., Lu, G.Q.M., Millar, G.J. (1996) Advances in mesoporous molecular sieve MCM-41. *Industrial Engineering Chemistry Research* (7) 2075 - 2090.

Zheng, Y., Wang, J., Liu, C., Lu, Y., Lin, X., Li, W., Zheng, Z. (2020) Optimizing Ni-Ce/HZSM-5 catalysts for ex-situ conversion of pine wood pyrolytic vapours into light aromatics and phenolic compounds. *International Journal of Hydrogen Energy* (45) 14728 – 14743.

Zhou, W. (2010) Reversed crystal growth: Implication for catalyst engineering. *Advanced Materials* (22) 3086 – 3092.