UNIVERSITI PUTRA MALAYSIA

ACTIVATED CARBON FROM OIL PALM MESOCARP FIBER FOR THE TREATMENT OF FINAL DISCHARGE OF PALM OIL EFFLUENT

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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 Master of Science

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Master of Science

ACTIVATED CARBON FROM OIL PALM MESOCARP FIBER FOR THE TREATMENT OF FINAL DISCHARGE OF PALM OIL EFFLUENT

By

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June 2016

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Malaysia palm oil industry produced abundant amounts of solid and liquid biomass annually. The current disposal practice is not environmentally friendly, with viable biomass for production of value added product being wasted. It is desirable to reuse the biomass as a feedstock for production of activated carbon and use it to treat palm oil mill final discharge to achieve zero emission system. This study aimed to reduce the COD and suspended solids content of palm oil mill final discharge using oil palm mesocarp fiber activated by steam and phosphoric acid.

The oil palm mesocarp fiber activated carbon was successfully produced either using steam and phosphoric acid as activating agents in a two-step process at a temperature of 600°C for 30 minutes. The resulting activated carbon BET surface area was found to be 494 and 1090 m^2/g, respectively, which are comparable to commercial activated carbon. The activated carbon also shows pore development compared to raw material from SEM analysis. Oil palm mesocarp fiber activated carbon was used to treat palm oil mill final discharge and the effect of adsorbent dosage, treatment time, adsorbate concentration and consecutive treatments was studied.

The oil palm mesocarp fiber activated carbon were able to reduce the COD and suspended solids content of the final discharge with a COD percent removal of 70% and 42 % for phosphoric acid and steam activated mesocarp fiber at 10 g/L dosage, respectively. For suspended solids, the removal percent was 85% and 81%, respectively. The amount of pollutant reduced increased as the adsorbent dosage increase and remained constant after 10 g/L. In terms of treatment time, as the treatment time increased, the amount of pollutants that were removed increased until a certain amount of time, which was found to be 6 hours for both COD and suspended solids content. For adsorbate concentration, as the COD

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initial concentration increased, reduction of pollutants for phosphoric acid activated carbon maintained, while steam activated carbon shows a higher reduction at lower concentration. For suspended solids, a similar effect was observed. The effect of consecutive treatment was also studied, with the increasing number of treatments resulting in a higher total reduction of pollutants. Consecutive small dosage treatment also proves to be more efficient compared to a single large dosage treatment.

It can be concluded that oil palm mesocarp fiber is a viable feedstock for activated carbon production, with resulting activated carbon able to reduce the pollutants in palm oil mill final discharge.

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Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

KARBON TERAKTIF DARIPADA SERAT MESOKARP KELAPA SAWIT UNTUK MERAWAT SISA BUANGAN AKHIR KILANG MINYAK SAWIT

Oleh

IZZUDIN IBRAHIM

Jun 2016

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Industri minyak sawit negara menghasilkan sisa biomas yang banyak sepanjang tahun. Kebanyakan biomas yang boleh dijadikan produk baru dibuang begitu sahaja dengan cara yang tidak mesra alam. Biomas itu boleh digunakan sebagai bahan asas untuk penghasilan karbon teraktif yang boleh digunakan untuk merawat sisa buangan akhir kilang minyak sawit untuk mencapai tarap system pelepasan sisa sifar. Kajian ini dijalankan untuk mengurangkan kandungan COD dan pepejal terampai didalam sisa buangan akhir kilang minyak sawit dengan menggunakan karbon teraktif dari serat mesocarp yang dihasilkan menggunakan pengaktifan wap air dan asid fosforik.

Karbon teraktif daripada serat mesokarp kelapa sawit berjaya dihasilkan dengan menggunakan wap air atau asid fosforik menggunakan proses dua langkah pada suhu 600°C selama 30 minit. Karbon teraktif yang terhasil mempunyai luas permukaan seperti karbon teraktif komersil, masing-masing mempunyai luas permukaan BET sebanyak 494 dan 1090 m^2/g. Perkembangan liang juga dapat dilihat melalui analisis SEM keatas serat mesocarp yang teraktif berbanding asal. Serat mesokarp kelapa sawit telah digunakan untuk merawat sisa buangan akhir kilang minyak sawit dan kesan dos penjerap, masa rawatan, kepekatan bahan terjerap dan rawatan berturutan turut dikaji.

Serat mesokarp kelapa sawit teraktif boleh mengurangkan kandungan COD dan pepejal terampai didalam sisa buangan akhir sebanyak 70% dan 42%, masing-masing untuk serat mesokarp yang diaktifkan menggunakan asid fosforik dan wap air pada dos 10 g/L. Untuk pepejal terampai, peratus pengurangan adalah masing-masing sebanyak 85% dan 81%.Peningkatan dos bahan penjerap dapat meningkatkan pengurangan bahan pencemar, dan kekal sama dengan penambahan dos melebihi 10 g/L.Ini adalah kerana pertindihan tapak penjerapan oleh partikel penjerap. Dari segi masa rawatan, semakin lama masa

rawatan, semakin tinggi pengurangan bahan cemar, dengan masa rawatan maksimum selama 6 jam untuk kedua-dua jenis pencemar. Ini adalah kerana tapak penjerapan pada bahan penjerap yang akan dipenuhi selepas satu tempoh masa. Dari segi kepekatan bahan terjerap, didapati bahawa kepekatan asal COD tidak memberi kesan yang signifikan terhadap pengurangan bahan pencemar bagi serat mesokarp diaktifkan dengan asid fosforik, manakala serat mesokarp diaktifkan dengan wap air menunjukkan pengurangan yang lebih tinggi dalam julat kepekatan rendah. Bagi pepejal terampai, kesan yang sama diperhatikan, dengan peningkatan kepekatan awal meningkatkan pengurangan pepejal terampai. Kesan rawatan berturutan turut dikaji, dengan peningkatan jumlah rawatan mengakibatkan jumlah pengurangan bahan pencemar menjadi lebih tinggi. Rawatan berturutan menggunakan dos yang kecil secara berturutan terbukti lebih baik berbanding rawatan menggunakan satu dos yang besar.

Dapat disimpulkan bahawa serat mesokarp kelapa sawit adalah bahan mentah yang sesuai untuk pengeluaran karbon teraktif, dengan karbon teraktif yang dihasilkan dapat mengurangkan bahan pencemar dalam sisa buangan akhir kilang minyak sawit.

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I certify that a Thesis Examination Committee has met on (date of viva voce) to conduct the final examination of Izzudin bin Ibrahim on his thesis entitled "Activated Carbon From Oil Palm Mesocarp Fiber For The Treatment Of Final Discharge Of Palm Oil Effluent" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A). 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science

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TABLE OF CONTENTS

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LIST OF TABLES

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LIST OF FIGURES

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LIST OF ABBREVIATIONS

ATR	Attenuated Total Reflectance
BET	Brunauer-Emmett-Teller
BOD	biological oxygen demand
CEFIC	The European Chemical Industry Council
COD	Chemical Oxygen Demand
CPO	Crude Palm Oil
DTA	Differential Thermal Analysis
DTG	Differential Thermogravimetric
FELDA	Federal Land Development Authority
FESEM	Field Emission Scanning Electron Microscopy
FTIR	Fourier Transform Infrared
GLC	Government Linked Company
HCl	Hydrochloric Acid
H_3PO_4	Phosphoric Acid
KBr	Potassium Bromide
KOH	Potassium Hydroxide
MDF	Medium Density Fiberboard
MMT	Million Metric Tonnes
MPOB	Malaysian Palm Oil Board
MPOC	Malaysian Palm Oil Council
NGO	Non-Governmental Organization
OPEFB	Oil Palm Empty Fruit Bunch
OPF	Oil Palm Frond

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OPMF	Oil Palm Mesocarp Fiber
OPT	Oil Palm Trunk
OPS	Oil Palm Shell
PAC	Polyaluminium Chloride
PKO	Palm Kernel Oil
POME	Palm Oil Mill Effluent
POMFD	Palm Oil Mill Final Discharge
POMS	Palm Oil Mill Sludge
Proton	Perbadanan Otomobil Nasional
PSD	Pore Size Distribution
SEM	Scanning Electron Microscopy
SS	Suspended Solids
STP	Standard Temperature and Pressure
TG	Thermogravimetric
$ZnCl_2$	Zinc Chloride

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CHAPTER 1

INTRODUCTION

Since the 1980s, Malaysia had become one of the largest producers and exporters of palm oil and its derivatives in the world, producing 19.79 million metric ton (MMT) of crude palm oil, and exporting 17.31 MMT of it to the world (Malaysian Palm Oil Board, 2014). Consequently, continuous mass production of palm oil creates by-products in the form of solid and liquid waste. Solid waste produced feasible trunks, fronds, empty fruit bunches, mesocarp fiber, kernel shell and press cake from oil extraction process while liquid waste produced are in the form of palm oil mill effluent (POME) and palm oil mill sludge (POMS).

The increasingly large amount of waste biomass produced every year leads to disposal problem. Currently, palm oil mills all around the country burned the waste biomass for energy in boilers (Ali *et al.*, 2015), or recycled as mulching in the palm oil plantation (Yoshizaki *et al.*, 2013). Older practices such as burning the empty fruit bunch to produce oil palm ash have been banned by the government due to its high pollution risks (Abdullah and Sulaiman, 2013). For liquid waste, aerobic treatment using large consecutive ponds in the palm oil mill was chosen due to its low cost and ability to reduce a significant amount of pollutant in the form of suspended solids (SS) and chemical oxygen demand (COD). This process produced palm oil mill final discharge (POMFD) or biologically treated palm oil mill effluent, which is then discarded to the main water body, usually rivers nearby (Othman *et al.*, 2014).

The current practice by the palm oil mills in Malaysia focused on the most economical method, or in other words, cheapest alternative available while at the same time adhering to the rules and regulations set by the government. The downside of this mentality is that the bad effects of such practice towards the environment are often neglected. For solid waste, the current practice promotes seepage of nutrients into the underground water and rivers from uncontrolled uses of mulch from palm oil biomass (Yoshizaki *et al.*, 2013) such as mesocarp fiber and empty fruit bunch. Uses of boilers to produce electricity by burning waste biomass increase the risk of pollution while inefficient boilers produce less electricity than is theoretically possible. On the other hand, discharge of effluent by palm oil mills is governed under the Environment Quality Act 1974 and its subsidiary legislation, where standard discharge limits for liquid effluent were outlined. There is no current federal legislation that governed the disposal of solid waste by the palm oil mills. Even though palm oil mill final discharge is safe to be disposed of according to the discharge limit, the high value of COD and visible color of the POMFD will increase the risk of eutrophication and reduce the aesthetics

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of the river water. It is evident that greener, more environmental-friendly method of disposing palm oil mill solid and liquid waste is needed.

The best solution for the problem at hand is to simultaneously dispose of both solid and liquid waste while reducing the effect on the environment. Better yet, treatment of the liquid waste reduces the amount of pollutant to the extent that it can be recycled back to the mill as feed water, while the disposal process of the solid waste produces value-added product that can be used to treat the liquid waste, in this case, POMFD. This concept was proposed by Othman *et al.*, (2014) where palm oil mill final discharge was treated until it reached river water quality so that it can be recycled back as feed water to the mill. Although the treatment was successful, the process uses commercial activated carbon and coagulants. This instead creates additional problems such as large amount of sludge to dispose and additional cost of using expensive activated carbon. The logical next step is to produce activated carbon from oil palm biomass, and use it to treat palm oil mill final discharge. Both disadvantages from previous research are solved while new value added product in the form of activated carbon is produced.

Presently, activated carbon is mass produced from coal, lignite, petroleum pitch or biomass such as coconut shells, via activation using physical or chemical activation agents. Biomass feedstock is first pyrolyzed at 700-1100°C under inert atmosphere (nitrogen or argon). Carbonized feedstock and other carbon precursor such as coal is then exposed to oxidizing atmosphere such as oxygen, carbon dioxide or steam at elevated temperature (600-1200°C). Another method of activation using chemical agents proceeds with impregnation of chemical agents onto the surface of the feedstock. Chemicals used are usually acid (phosphoric acid, H_3PO_4), strong base (potassium hydroxide, KOH) or salt (zinc chloride, $ZnCl_2$). Impregnated feedstock is then carbonized at temperature of about 450-900°C, where carbonization and activation happened simultaneously (Yahya *et al.*, 2015).

Researchers have been investigating the feasibility of using biomass as feedstock for biochar and activated carbon production. A study by Agirre *et al.*, (2013) uses fruit cuttings from Extremadura as feedstock for production of charcoal using screw pyrolysis reactor. The resulting charcoal produced was determined to be suitable for use as reducing agent in metal production due to excellent high carbon content. Another research by Rashidi *et al.*, (2012) activates palm kernel shell, palm mesocarp fiber, rice husk, coconut shell and coconut fiber using carbon dioxide. Activated samples show high porosity through field emission scanning electron microscopy (FESEM) analysis with a yield of about 20%. Even though the research shows the feasibility of oil palm biomass in terms of palm kernel shell and oil palm mesocarp fiber as a precursor for activated carbon production, there is a few problems that needs to be addressed. In terms of biomass, palm kernel shell

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is a good precursor due to its high carbon content but its high current price with large reduction of final product weight after activation, will results in loss of revenue to the palm oil mills. The activation agents chosen which is carbon dioxide, adds to the cost of the process compared to using readily available resources in the mills such as excess steam from the sterilization process. Uses of fibers such as oil palm mesocarp fiber and steam as its activating agents can effectively reduce the cost of production, in which will increase the revenue that can be made from the activated carbon.

Although multiple types of biomass have been studied, due to the diverse method of activation used, no significant comparison can be made between each research. In addition to that, no large scale application of previous research has been done, inhibiting progress towards implementation of biomass activated carbon production technology in the industry.

This research is expected to be able to produce activated carbon from oil palm biomass with comparable quality to commercially activated carbon. Activated carbon produced are expected to have Brunauer-Emmett-Teller (BET) surface area of 500 m^2/g or above for wastewater treatment utilization. It is also expected that the activated carbon produced is able to treat palm oil mill final discharge effectively, by reducing the residual pollutants in the final discharge down, until it reaches river water quality for use as recycled water in the palm oil mill.

The overall objective of this research is to produce activated carbon with a minimum surface area of 500 m^2/g from oil palm biomass using carbonization and activation. This research also targeted that the activated carbon produced can treat palm oil mill final discharge effectively.

Specific objectives:

- To produce activated carbon using oil palm mesocarp fiber via carbonization, physical and chemical activation with at least 500 m^2/g surface area.
- To characterize the activated carbon produced in terms of BET surface area, pore size and volume, surface functional groups, and its thermogravimetric properties.
- To determine the performance of activated carbon produced in treating palm oil mill final discharge.

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REFERENCES

Abbasi, T., and Abbasi, S. a. (2010). Biomass energy and the environmental impacts associated with its production and utilization. *Renewable and Sustainable Energy Reviews*, *14*(3), 919–937.

Abdullah, N., and Sulaiman, F. (2013). The Oil Palm Wastes in Malaysia. In M. D. Matovic (Ed.), *Biomass Now - Sustainable Growth and Use* (1st ed., pp. 75–100). InTech.

Abdurahman, N. H., Rosli, Y. M., and Azhari, N. H. (2013). *International Perspectives on Water Quality Management and Pollutant Control*. (N. W. T. Quinn, Ed.). InTech.

Agirre, I., Griessacher, T., Rösler, G., and Antrekowitsch, J. (2013). Production of charcoal as an alternative reducing agent from agricultural residues using a semi-continuous semi-pilot scale pyrolysis screw reactor. *Fuel Processing Technology*, *106*, 114–121.

Agrafioti, E., Bouras, G., Kalderis, D., and Diamadopoulos, E. (2013). Biochar production by sewage sludge pyrolysis. *Journal of Analytical and Applied Pyrolysis*, *101*, 72–78.

Alam, M. Z., Ameem, E. S., Muyibi, S. a., and Kabbashi, N. a. (2009). The factors affecting the performance of activated carbon prepared from oil palm empty fruit bunches for adsorption of phenol. *Chemical Engineering Journal*, *155*(1-2), 191–198.

Ali, A. A. M., Othman, M. R., Shirai, Y., and Hassan, M. A. (2015). Sustainable and integrated palm oil biorefinery concept with value-addition of biomass and zero emission system. *Journal of Cleaner Production*, *91*, 96–99.

Angın, D. (2013). Effect of pyrolysis temperature and heating rate on biochar obtained from pyrolysis of safflower seed press cake. *Bioresource Technology*, *128*, 593–597.

Babel, S. (2003). Low-cost adsorbents for heavy metals uptake from contaminated water: a review. *Journal of Hazardous Materials*, *97*(1-3), 219–243.

Baharuddin, A. S., Aini, N., Rahman, A., Shah, U. K., and Ali, M. (2011). Evaluation of pressed shredded empty fruit bunch (EFB) -palm oil mill effluent (POME) anaerobic sludge based compost using Fourier transform infrared (FTIR) and nuclear magnetic resonance (NMR) analysis. *African Journal of Biotechnology*, *10*(41), 8082–8089.

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Bandosz, T. J. (2008). *Removal of inorganic gases and VOCs on activated carbons*. *Adsorption by Carbons*. Elsevier.

Baskaran, M., Hashim, R., Said, N., Raffi, S. M., Balakrishnan, K., Sudesh, K., … Sato, M. (2012). Properties of binderless particleboard from oil palm trunk with addition of polyhydroxyalkanoates. *Composites Part B: Engineering*, *43*(3), 1109–1116.

Bews, I. M., Hayhurst, A. N., Richardson, S. M., and Taylor, S. G. (2001). The order, Arrhenius parameters, and mechanism of the reaction between gaseous oxygen and solid carbon. *Combustion and Flame*, *124*(1-2), 231–245.

biomass | biology | Britannica.com. (2015). Retrieved January 4, 2016, from http://www.britannica.com/science/biomass

Bond, G. R. (2002). The role of activated charcoal and gastric emptying in gastrointestinal decontamination: A state-of-the-art review. *Annals of Emergency Medicine*, *39*(3), 273–286.

Bottani, E. J., and Tascon, J. M. D. (2008). *Adsorption by Carbons* (1st ed.). Elsevier LtdOxford, UK.

Bouchelta, C., Medjram, M. S., Bertrand, O., and Bellat, J.-P. (2008). Preparation and characterization of activated carbon from date stones by physical activation with steam. *Journal of Analytical and Applied Pyrolysis*, *82*(1), 70–77.

Brunauer, S., Emmett, P. H., and Teller, E. (1938). Adsorption of gases in multimolecular layers. *Journal of the American Chemical Society*, *60*(2), 309–319.

Cheremisinoff, N. P. (2002). *Handbook of Water and Wastewater Treatment Technologies*. Butterworth-Heinemann.

Chin, K. K., Ng, W. J., and Ma, A. N. (1987). Palm oil refinery effluent treatment by sequencing batch reactors. *Biological Wastes*, *20*(2), 101–109.

Corley, R. H. V., and Tinker, P. B. (2003). *The Oil Palm*. (R. H. V. Corley & P. B. Tinker, Eds.). Blackwell Science LtdOxford, UK.

Costa, A. G., Pinheiro, G. C., Pinheiro, F. G. C., Dos Santos, A. B., Santaella, S. T., and Leitão, R. C. (2013). Pretreatment strategies to improve anaerobic biodegradability and methane production potential of the palm oil mesocarp fibre. *Chemical Engineering Journal*, *230*, 158–165.

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Dabrowski, A., Podkościelny, P., Hubicki, Z., and Barczak, M. (2005). Adsorption of phenolic compounds by activated carbon--a critical review. *Chemosphere*, *58*(8), 1049–1070.

Department of Environment Malaysia. (1982). Environment Quality Act 1974-Environment Quality (Prescribed Premises)(Crude Palm Oil)(Amendment) Regulations 1982. Malaysia: Department of Enviroment, Malaysia. Retrieved February 20, 2015, from http://www.doe.gov.my/portalv1/wp-content/plugins/download-attachments/includes/download.php?id=317498

Dias, J. M., Alvim-Ferraz, M. C. M., Almeida, M. F., Rivera-Utrilla, J., and Sánchez-Polo, M. (2007). Waste materials for activated carbon preparation and its use in aqueous-phase treatment: a review. *Journal of Environmental Management*, *85*(4), 833–846.

Dipanfilo, R., and Egiebor, N. (1996). Activated carbon production from synthetic crude coke. *Fuel Processing Technology*, *46*, 157–169.

Doğan, M., and Alkan, M. (2003). Adsorption kinetics of methyl violet onto perlite. *Chemosphere*, *50*(4), 517–528.

Doğan, M., Alkan, M., Türkyilmaz, A., and Ozdemir, Y. (2004). Kinetics and mechanism of removal of methylene blue by adsorption onto perlite. *Journal of Hazardous Materials*, *B109*, 141–148.

El-Hendawy, A.-N. A. (2006). Variation in the FTIR spectra of a biomass under impregnation, carbonization and oxidation conditions. *Journal of Analytical and Applied Pyrolysis*, *75*(2), 159–166.

Er, A. C., Nor, A. R., and Rostam, K. (2011). Palm Oil Milling Wastes and Sustainable Development. *American Journal of Applied Sciences*, *8*(5), 436–440.

FAO. (1990). *Better Farming Series: The Oil Palm*. *FAO Economic and Social Development Series* (3rd ed.). Food and Agriculture Organization of the United Nations. Retrieved from http://www.fao.org/docrep/006/t0309e/t0309e01.htm

Fierro, V., Torné-Fernández, V., and Celzard, A. (2007). Methodical study of the chemical activation of Kraft lignin with KOH and NaOH. *Microporous and Mesoporous Materials*, *101*(3), 419–431.

Fitzer, E., Kochling, K.-H., Boehm, H. P., and Marsh, H. (1995). Recommended terminology for the description of carbon as a solid (IUPAC Recommendations 1995). *Pure and Applied Chemistry*, *67*(3), 473–506.

© COPYRIGHT UPM

Foo, K. Y., and Hameed, B. H. (2010). Insight into the applications of palm oil mill effluent: A renewable utilization of the industrial agricultural waste. *Renewable and Sustainable Energy Reviews*, *14*(5), 1445–1452.

Foo, K. Y., Lee, L. K., and Hameed, B. H. (2013). Batch adsorption of semi-aerobic landfill leachate by granular activated carbon prepared by microwave heating. *Chemical Engineering Journal*, *222*, 259–264.

Frankcombe, T. J., and Smith, S. C. (2004). On the microscopic mechanism of carbon gasification: A theoretical study. *Carbon*, *42*(14), 2921–2928.

Fun, C. W., Haq, M. R. U., and Kutty, S. R. M. (2007). Treatment of palm oil mill effluent using biological sequencing batch reactor system. In K. L. Brebbia, C. A.;Katsifarakis (Ed.), *River basin management IV, Kos, Greece, May 2007* (pp. 511–518).

Gandhidasan, P., Alfarayedhi, A. A., and Al-Mubarak, A. A. (2001). Dehydration of natural gas using solid desiccants. *Energy*, *26*(9), 855–868.

Garrido, J., Linares-Solano, A., Martin-Martinez, J. M., Molina-Sabio, M., Rodriguez-Reinoso, F., and Torregrosa, R. (1987). Use of nitrogen vs. carbon dioxide in the characterization of activated carbons. *Langmuir*, *3*(1), 76–81.

Girgis, B. S., and El-Hendawy, A.-N. A. (2002). Porosity development in activated carbons obtained from date pits under chemical activation with phosphoric acid. *Microporous and Mesoporous Materials*, *52*(2), 105–117.

Goh, C. S., Tan, K. T., Lee, K. T., and Bhatia, S. (2010). Bio-ethanol from lignocellulose: Status, perspectives and challenges in Malaysia. *Bioresource Technology*, *101*(13), 4834–41.

Gonzalez, J. C., Gonzalez, M. T., Molina-Sabio, M., Rodriguez-Reinoso, F., and Sepulveda-Escribano, A. (1995). Porosity of activated carbons prepared from different lignocellulosic materials. *Carbon*, *33*(8), 1175–1177.

Goud, V. V., Mohanty, K., Rao, M. S., and Jayakumar, N. S. (2005). Phenol Removal from Aqueous Solutions by Tamarind Nutshell Activated Carbon: Batch and Column Studies. *Chemical Engineering & Technology*, *28*(7), 814–821.

Hadi, P., To, M.-H., Hui, C.-W., Lin, C. S. K., and McKay, G. (2015). Aqueous mercury adsorption by activated carbons. *Water Research*, *73*, 37–55.

© COPYRIGHT UPM

Hamza, U. D., Nasri, N. S., Amin, N. S., Mohammed, J., and Zain, H. M. (2015). Characteristics of oil palm shell biochar and activated carbon prepared at different carbonization times. *Desalination and Water Treatment*, 1–8.

Han, Z., Sani, B., Akkanen, J., Abel, S., Nybom, I., Karapanagioti, H. K., and Werner, D. (2015). A critical evaluation of magnetic activated carbon's potential for the remediation of sediment impacted by polycyclic aromatic hydrocarbons. *Journal of Hazardous Materials*, *286*, 41–47.

Hassler, J. W. (1974). *Purification with Activated Carbon: Industrial, Commercial, Environmental* (3rd ed.). Chemical Publishing Company.

Hayden, J. W., and Comstock, E. G. (2008). Use of Activated Charcoal in Acute Poisoning. *Clinical Toxicology*, *8*(5), 515–533.

Heidari, A., Younesi, H., Rashidi, A., and Ghoreyshi, A. (2013). Adsorptive removal of CO2 on highly microporous activated carbons prepared from Eucalyptus camaldulensis wood: Effect of chemical activation. *Journal of the Taiwan Institute of Chemical Engineers*.

Hock, L. S., Baharuddin, A. S., Ahmad, M. N., Shah, U. K., Aini, N., Rahman, A., … Shirai, Y. (2009). Physicochemical Changes in Windrow Co-Composting Process of Oil Palm Mesocarp Fiber and Palm Oil Mill Effluent Anaerobic Sludge. *Australian Journal of Basic and Applied Sciences*, *3*(3), 2809–2816.

Iakovou, E., Karagiannidis, A., Vlachos, D., Toka, A., and Malamakis, A. (2010). Waste biomass-to-energy supply chain management: a critical synthesis. *Waste Management*, *30*(10), 1860–1870.

Idris, S. S., Abd Rahman, N., Ismail, K., Alias, A. B., Abd Rashid, Z., and Aris, M. J. (2010a). Investigation on thermochemical behaviour of low rank Malaysian coal, oil palm biomass and their blends during pyrolysis via thermogravimetric analysis (TGA). *Bioresource technology*, *101*(12), 4584–92.

Idris, S. S., Abd Rahman, N., Ismail, K., Alias, A. B., Abd Rashid, Z., and Aris, M. J. (2010b). Investigation on thermochemical behaviour of low rank Malaysian coal, oil palm biomass and their blends during pyrolysis via thermogravimetric analysis (TGA). *Bioresource Technology*, *101*(12), 4584–4592.

Igwe, J. C., and Onyegbado, C. C. (2007). A Review of Palm Oil Mill Effluent (Pome) Water Treatment. *Global Journal of Environmental Research*, *1*(2), 54–62.

Ioannidou, O., and Zabaniotou, a. (2007). Agricultural residues as precursors for activated carbon production—A review. *Renewable and Sustainable Energy Reviews*, *11*(9), 1966–2005.

© COPYRIGHT UPM

Ishak, W. I. W., and Hudzari, R. M. (2010). Image based modeling for oil palm fruit maturity prediction. *Journal of Food, Agriculture and Environment*, *8*(2), 469–476.

Izquierdo, M. T., Martínez de Yuso, A., Rubio, B., and Pino, M. R. (2011). Conversion of almond shell to activated carbons: Methodical study of the chemical activation based on an experimental design and relationship with their characteristics. *Biomass and Bioenergy*, *35*(3), 1235–1244.

Jagtoyen, M., and Derbyshire, F. (1998). Activated carbons from yellow poplar and white oak by H3PO4 activation. *Carbon*, *36*(7-8), 1085–1097.

John, M. J., and Thomas, S. (2008). Biofibres and biocomposites. *Carbohydrate Polymers*, *71*(3), 343–364.

Joos, P., and Serrien, G. (1991). The principle of Braun—Le Châtelier at surfaces. *Journal of Colloid and Interface Science*, *145*(1), 291–294.

Jumasiah, a., Chuah, T. G., Gimbon, J., Choong, T. S. Y., and Azni, I. (2005). Adsorption of basic dye onto palm kernel shell activated carbon: sorption equilibrium and kinetics studies. *Desalination*, *186*(1-3), 57–64.

Langmuir, I. (1918). The adsorption of gases on plane surfaces of glass, mica and platinum. *Journal of the American Chemical Society*, *40*(9), 1361–1403.

Larabi, C., al Maksoud, W., Szeto, K. C., Roubaud, A., Castelli, P., Santini, C. C., and Walter, J. J. (2013). Thermal decomposition of lignocellulosic biomass in the presence of acid catalysts. *Bioresource Technology*, *148*, 255–260.

Li, Y., Du, Q., Liu, T., Peng, X., Wang, J., Sun, J., … Xia, L. (2013). Comparative study of methylene blue dye adsorption onto activated carbon, graphene oxide, and carbon nanotubes. *Chemical Engineering Research and Design*, *91*(2), 361–368.

Liu, Q.-S., Zheng, T., Wang, P., and Guo, L. (2010). Preparation and characterization of activated carbon from bamboo by microwave-induced phosphoric acid activation. *Industrial Crops and Products*, *31*(2), 233–238.

Malaysian Palm Oil Board. (2014). Overview of the Malaysian Oil Palm Industry 2014. *Overview of the Malaysian Oil Palm Industry 2014*.

Marsh, H., and Rodriguez-Reinoso, F. (2006). *Activated Carbon* (1st ed.). Elsevier Ltd London.

© COPYRIGHT UPM

Masel, R. I. (1996). *Principles of Adsorption and Reaction on Solid Surfaces*. John Wiley & Sons.

McBain, J. W. (1933). The Sorption of Gases and Vapours by Solids. *Journal of Physical Chemistry*, *37*(1), 149–150.

Mckendry, P. (2002). Energy production from biomass (part 1): overview of biomass. *Bioresource Technology*, *83*, 37–46.

Mekhilef, S., Saidur, R., Safari, a., and Mustaffa, W. E. S. B. (2011). Biomass energy in Malaysia: Current state and prospects. *Renewable and Sustainable Energy Reviews*, *15*(7), 3360–3370.

Meyer, S., Glaser, B., and Quicker, P. (2011). Technical , Economical , and Climate-Related Aspects of Biochar Production Technologies : A Literature Review. *Environmental Science and Technology*, *45*, 9473–9483.

Misra, M., Pandey, J. K., and Mohanty, A. (2015). *Biocomposites: Design and Mechanical Performance* (1st ed.). Elsevier Science.

Mochida, I., Korai, Y., Shirahama, M., Kawano, S., Hada, T., Seo, Y., … Yasutake, A. (2000). Removal of SOx and NOx over activated carbon fibers. *Carbon*, *38*(2), 227–239.

Mohammed, R. R., and Chong, M. F. (2014). Treatment and decolorization of biologically treated Palm Oil Mill Effluent (POME) using banana peel as novel biosorbent. *Journal of Environmental Management*, *132*, 237–249.

Mohan, D., Singh, K. P., Sinha, S., and Gosh, D. (2005). Removal of pyridine derivatives from aqueous solution by activated carbons developed from agricultural waste materials. *Carbon*, *43*(8), 1680–1693.

Mohan, S. V., and Karthikeyan, J. (1997). Removal of lignin and tannin colour from aqueous solution by adsorption onto activated charcoal. *Environmental Pollution*, *97*(1-2), 183–187.

Mokhatab, S., Poe, W. A., and Mak, J. Y. (2015). *Handbook of Natural Gas Transmission and Processing: Principles and Practices* (3rd ed.). Gulf Professional Publishing.

Molina-Sabio, M., and Rodríguez-Reinoso, F. (2004). Role of chemical activation in the development of carbon porosity. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *241*(1-3), 15–25.

Molina-Sabio, M., RodRíguez-Reinoso, F., Caturla, F., and Sellés, M. J. (1995). Porosity in granular carbons activated with phosphoric acid. *Carbon*, *33*(8), 1105–1113.

© COPYRIGHT UPM

Naik, S. N., Goud, V. V, Rout, P. K., and Dalai, A. K. (2010). Production of first and second generation biofuels : A comprehensive review. *Renewable and Sustainable Energy Reviews*, *14*, 578–597.

Neuvonen, P. J., and Olkkola, K. T. (2012). Oral Activated Charcoal in the Treatment of Intoxications. *Medical Toxicology and Adverse Drug Experience*, *3*(1), 33–58.

Ng, C., Marshall, W., Rao, R. M., Bansode, R. R., Losso, J. N., and Portier, R. J. (2003). *Granular Activated Carbons from Agricultural By-products : Process Description and Estimated Cost of Production*.

Ngoc, U. N., and Schnitzer, H. (2009). Sustainable solutions for solid waste management in Southeast Asian countries. *Waste Management*, *29*(6), 1982–1995.

Nguyen, T. V., Jeong, S., Pham, T. T. N., Kandasamy, J., and Vigneswaran, S. (2014). Effect of granular activated carbon filter on the subsequent flocculation in seawater treatment. *Desalination*, *354*, 9–16.

Nordin, N., Ariffin, H., Andou, Y., Hassan, M., Shirai, Y., Nishida, H., … Ibrahim, N. (2013). Modification of Oil Palm Mesocarp Fiber Characteristics Using Superheated Steam Treatment. *Molecules*, *18*(8), 9132–9146.

Nunes, C. A., and Guerreiro, M. C. (2011). Estimation of surface area and pore volume of activated carbons by methylene blue and iodine numbers. *Química Nova*, *34*(3), 472–476.

Okhovat, A., Ahmadpour, A., Ahmadpour, F., and Khaki Yadegar, Z. (2012). Pore Size Distribution Analysis of Coal-Based Activated Carbons: Investigating the Effects of Activating Agent and Chemical Ratio. *ISRN Chemical Engineering*, *2012*, 1–10.

Othman, M. R., Hassan, M. A., Shirai, Y., Baharuddin, A. S., Ali, A. A. M., and Idris, J. (2014). Treatment of effluents from palm oil mill process to achieve river water quality for reuse as recycled water in a zero emission system. *Journal of Cleaner Production*, *67*, 58–61.

Pimentel, D. (2002). Limits of Biomass Utilization. In *Encyclopedia of Physical Science and Technology*. Academic Press.

Poku, K. (2002). *Small-Scale Palm Oil Processing in Africa* (1st ed.). Food and Agriculture Organization of the United Nations. Retrieved from http://www.fao.org/docrep/005/y4355e/y4355e03.htm

Pollard, S. J. T., Fowler, G. D., Sollars, C. J., and Perry, R. (1992). Low-cost adsorbents for waste and wastewater treatment: A review. *Science of the Total Environment*, *116*(1-2), 31–52.

© COPYRIGHT UPM

Prins, M. J., Ptasinski, K. J., and Janssen, F. J. J. G. (2003). Thermodynamics of gas-char reactions: first and second law analysis. *Chemical Engineering Science*, *58*(3-6), 1003–1011.

Puziy, A. ., Poddubnaya, O. ., Martínez-Alonso, A., Suárez-García, F., and Tascón, J. M. . (2002). Synthetic carbons activated with phosphoric acid. *Carbon*, *40*(9), 1493–1505.

Rashidi, N. A., and Yusup, S. (2016). An overview of activated carbons utilization for the post-combustion carbon dioxide capture. *Journal of CO2 Utilization*, *13*, 1–16.

Rashidi, N. A., Yusup, S., Ahmad, M. M., Mohamed, N. M., and Hameed, B. H. (2012). Activated Carbon from the Renewable Agricultural Residues Using Single Step Physical Activation: A Preliminary Analysis. *APCBEE Procedia*, *3*, 84–92.

Román, S., Ledesma, B., González, J. F., Al-Kassir, A., Engo, G., and Álvarez-Murillo, A. (2013). Two stage thermal regeneration of exhausted activated carbons. Steam gasification of effluents. *Journal of Analytical and Applied Pyrolysis*, *103*, 201–206.

Rossetti, I., Ramis, G., Gallo, A., and Di Michele, A. (2015). Hydrogen storage over metal-doped activated carbon. *International Journal of Hydrogen Energy*, *40*(24), 7609–7616.

Rupani, P. F., Singh, R. P., Ibrahim, M. H., and Esa, N. (2010). Review of Current Palm Oil Mill Effluent (POME) Treatment Methods : Vermicomposting as a Sustainable Practice. *World Applied Sciences Journal*, *11*(1), 70–81. Retrieved from http://www.idosi.org/wasj/wasj11(1)10/12.pdf

Ruthven, D. M. (1984). *Principles of Adsorption and Adsorption Processes* (1st ed.). John Wiley & Sons.

Saidu, M., Yuzir, A., Salim, M. R., Azman, S., and Abdullah, N. (2014). Biological pre-treated oil palm mesocarp fibre with cattle manure for biogas production by anaerobic digestion during acclimatization phase. *International Biodeterioration & Biodegradation*, *95*, 189–194.

Seaton, N. A., Walton, J. P. R. B., and quirke, N. (1989). A new analysis method for the determination of the pore size distribution of porous carbons from nitrogen adsorption measurements. *Carbon*, *27*(6), 853–861.

Shaarani, F. W., and Hameed, B. H. (2010). Batch adsorption of 2,4-dichlorophenol onto activated carbon derived from agricultural waste. *Desalination*, *255*(1-3), 159–164.

© COPYRIGHT UPM

Shinoj, S., Visvanathan, R., Panigrahi, S., and Kochubabu, M. (2011). Oil palm fiber (OPF) and its composites: A review. *Industrial Crops and Products*, *33*(1), 7–22.

Shuit, S. H., Tan, K. T., Lee, K. T., and Kamaruddin, a. H. (2009). Oil palm biomass as a sustainable energy source: A Malaysian case study. *Energy*, *34*(9), 1225–1235.

Sudaryanto, Y., Hartono, S. B., Irawaty, W., Hindarso, H., and Ismadji, S. (2006). High surface area activated carbon prepared from cassava peel by chemical activation. *Bioresource Technology*, *97*(5), 734–739.

Sumathi, S., Chai, S. P., and Mohamed, a. R. (2008). Utilization of oil palm as a source of renewable energy in Malaysia. *Renewable and Sustainable Energy Reviews*, *12*(9), 2404–2421.

Then, Y. Y., Ibrahim, N. A., Zainuddin, N., Ariffin, H., Yunus, W. M. Z. W., and Chieng, B. W. (2014). The influence of green surface modification of oil palm mesocarp fiber by superheated steam on the mechanical properties and dimensional stability of oil palm mesocarp fiber/poly(butylene succinate) biocomposite. *International Journal of Molecular Sciences*, *15*, 15344–15357.

Tsai, W. T., Chang, C. Y., and Lee, S. L. (1997). Preparation and characterization of activated carbons from corn cob. *Carbon*, *35*(8), 1198–1200.

U.S. Department of Energy. (2011). *US Billion Ton Update: Supply for a Bioenergy and Bioprodcts Industry*. Oak Ridge.

Uemura, Y., Omar, W. N., Tsutsui, T., and Yusup, S. B. (2011). Torrefaction of oil palm wastes. *Fuel*, *90*(8), 2585–2591.

University of Kentucky Center for Applied Energy Research - Carbon Materials - Carbon History and Timeline. (2015). Retrieved January 1, 2016,from http://www.caer.uky.edu/carbon/history/carbonhistory.shtml

Vamvuka, D., Kakaras, E., Kastanaki, E., and Grammelis, P. (2003). Pyrolysis characteristics and kinetics of biomass residuals mixtures with lignite. *Fuel*, *82*(15-17), 1949–1960.

Verma, V. K., and Mishra, A. K. (2008). Removal of dyes using low cost adsorbent. *Indian Journal of Chemical Technology*, *15*, 140–145. Retrieved from http://nopr.niscair.res.in/handle/123456789/886

Vijayaraghavan, K., Ahmad, D., and Ezani Bin Abdul Aziz, M. (2007). Aerobic treatment of palm oil mill effluent. *Journal of Environmental Management*, *82*(1), 24–31.

© COPYRIGHT UPM

Volatile Matter. (2016). Retrieved June 27, 2016, from https://www.corrosionpedia.com/definition/1153/volatile-matter

Wang, L., Zhang, J., Liu, J., He, H., Yang, M., Yu, J., … Jiang, F. (2010). Removal of bromate ion using powdered activated carbon. *Journal of Environmental Sciences*, *22*(12), 1846–1853.

Yahya, M. A., Al-Qodah, Z., and Ngah, C. W. Z. (2015). Agricultural bio-waste materials as potential sustainable precursors used for activated carbon production: A review. *Renewable and Sustainable Energy Reviews*, *46*, 218–235.

Yang, H., Yan, R., Chen, H., Lee, D. H., and Zheng, C. (2007). Characteristics of hemicellulose, cellulose and lignin pyrolysis. *Fuel*, *86*(12-13), 1781–1788.

Yong, Z., Mata, V., and Rodrigues, A. E. (2002). Adsorption of carbon dioxide at high temperature—a review. *Separation and Purification Technology*, *26*(2-3), 195–205.

Yoshizaki, T., Shirai, Y., Hassan, M. A., Baharuddin, A. S., Raja Abdullah, N. M., Sulaiman, A., and Busu, Z. (2013). Improved economic viability of integrated biogas energy and compost production for sustainable palm oil mill management. *Journal of Cleaner Production*, *44*, 1–7.

Young, P. M., Roberts, D., Chiou, H., Rae, W., Chan, H.-K., and Traini, D. (2008). Composite carriers improve the aerosolisation efficiency of drugs for respiratory delivery. *Journal of Aerosol Science*, *39*(1), 82–93.

Zahari, M. A. K. M., Zakaria, M. R., Ariffin, H., Mokhtar, M. N., Salihon, J., Shirai, Y., and Hassan, M. A. (2012). Renewable sugars from oil palm frond juice as an alternative novel fermentation feedstock for value-added products. *Bioresource Technology*, *110*, 566–571.

Zainudin, Z. (2010). Benchmarking river water quality in Malaysia. *Jurutera*, (February), 12–15.

Zakaria, M. R., Hirata, S., Fujimoto, S., Ibrahim, I., and Hassan, A. (2016). Soluble inhibitors generated during hydrothermal pretreatment of oil palm mesocarp fiber suppressed the catalytic activity of Acremonium cellulase. *Bioresource Technology*, *200*, 541–547.

Zhang, Y.-J., Ou, J.-L., Duan, Z.-K., Xing, Z.-J., and Wang, Y. (2015). Adsorption of Cr(VI) on bamboo bark-based activated carbon in the absence and presence of humic acid. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *481*, 108–116.

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