UNIVERSITI PUTRA MALAYSIA

BLENDS OF POLYACRYLONITRILE AND LIGNIN OF SAGO WASTE FOR PRODUCTION OF CARBON NANOFIBERS FOR REMOVAL OF LEAD(II) FROM AQUEOUS SOLUTION

NURUL AIDA BINTI NORDIN

FS 2020 51

BLENDS OF POLYACRYLONITRILE AND LIGNIN OF SAGO WASTE FOR PRODUCTION OF CARBON NANOFIBERS FOR REMOVAL OF LEAD(II) FROM AQUEOUS SOLUTION

By

NURUL AIDA BINTI NORDIN

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

November 2019

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

BLENDS OF POLYACRYLONITRILE AND LIGNIN OF SAGO WASTE FOR PRODUCTION OF CARBON NANOFIBERS FOR REMOVAL OF LEAD(II) FROM AQUEOUS SOLUTION

By

NURUL AIDA BINTI NORDIN

November 2019

Chairman : Norizah Abdul Rahman, PhD
Faculty : Science

Heavy metal pollution such as lead(II) tends to cause serious environmental problems and brought toxicity effect to human and indicates that an effort must be taken in order to reduce its concentration in waste water effluents. Adsorption was proven to be economical and efficient to remove heavy metals in aqueous solution compared to other methods. There is an increasing amount of research focusing on the use of waste materials as adsorbents, aligned with the environmental protection awareness. In this study, activated carbon nanofibers (ACNFs) were produced from blends of polyacrylonitrile (PAN) and lignin of sago waste via electrospinning technique for the removal of Pb(II) ions from aqueous solution. PAN/SL ACNFs was characterized by different spectroscopic techniques and the application of PAN/SL ACNFs as the adsorbent for removal of Pb(II) ions from aqueous solution was increased three times after activation. The activation of PAN/SL ACNFs with nitric acid resulted in the attachments of oxygenated functional groups that responsible for the decreased in hydrophobicity thus promoting the metal adsorption in aqueous solution. The equilibrium time of adsorption of PAN/SL ACNFs towards Pb(II) ions was achieved in 240 mins by using 40 mg of adsorbent. The effect of initial concentration of Pb(II) was studied and the removal of Pb(II) ions from 125 mg/L solution was almost reached the monolayer coverage with the value of 555.56 mg/g. The adsorption was also dependent on the pH of the solution and the percentage removal was higher at pH 5 — 6 with 66.9 and 67.6% of Pb(II) removal. It was observed that pseudo-second order kinetic model was well-fitted with the experimental data which indicated that the adsorption process was controlled by chemisorption. The adsorption behaviour were best described by Langmuir isotherm model in which the q_{max} was 588.24 mg/g. From the intra-particle diffusion multilinear plot, it was suggested that two steps of adsorption were involved in the adsorption of Pb(II) ions. Therefore, in this study the adsorbent was successfully prepared from the blended of PAN and lignin of sago

waste and PAN/SL ACNFs have a potential to be used as the adsorbent for the removal of Pb(**II**) from aqueous solution.

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

CAMPURAN POLYAKRYLONITRIL DAN LIGNIN DARIPADA SISA SAGU UNTUK PENGHASILAN KARBON NANOFIBER BAGI MENYINGKIRKAN PLUMBUM(II) DARIPADA LARUTAN AKUES

Oleh

NURUL AIDA BINTI NORDIN

November 2019

Pengerusi : Norizah Abdul Rahman, PhD
Fakulti : Sains

Pencemaran logam berat seperti plumbum(II) cenderung untuk menyebabkan masalah alam sekitar yang serius dan membawa kesan toksik kepada manusia dan ini menunjukkan bahawa usaha perlu diambil untuk mengurangkan kepekatan plumbum(II) dalam cecair sisa air. Penjerapan telah terbukti sebagai jimat dan efisien untuk menyingkirkan logam berat di dalam larutan akues berbanding kaedah-kaedah lain. Terdapat peningkatan dalam penyelidikan yang memberi fokus kepada penggunaan bahan buangan sebagai penjerap, sejajar dengan kesedaran untuk melindungi alam sekitar. Dalam kajian ini, karbon nanofiber yang aktif (ACNFs) telah dihasilkan daripada campuran polyakrylonitril (PAN) dan lignin daripada sisa sagu melalui teknik elektrospining untuk menyingkirkan Pb(II) daripada larutan akues. PAN/SL ACNFs telah dicirikan melalui teknik spektroskopi yang berbeza dan aplikasi PAN/SL ACNFs sebagai penjerap untuk penyingkiran ion-ion Pb(II) daripada larutan akues telah meningkat tiga kali selepas pengaktifan. Pengaktifan PAN/SL ACNFs menggunakan asid nitrik telah menyebabkan pelekatan kumpulan berfungsi beroksigen yang bertanggungjawab kepada penurunan sifat hydrofobik dan seterusnya menggalakkan penjerapan logam dalam larutan akues. Masa keseimbangan untuk penjerapan PAN/SL ACNFs terhadap ion-ion Pb(II) telah dicapai dalam masa 240 minit dengan menggunakan 40 mg penjerap. Kesan kepekatan permulaan Pb(II) telah dikaji dan penyingkiran ion-ion Pb(II) daripada larutan 125 mg/L adalah hampir meliputi lapisan tunggal dengan nilai 555.56 mg/g. Penjerapan ini juga bergantung kepada pH larutan dan peratusan penyingkiran adalah lebih tinggi pada pH 5 — 6 dengan 66.9 dan 67.6% Pb(II) yang disingkir. Model kinetik pseudo kedua telah diperhatikan sangat bersesuaian dengan data eksperimen yang menunjukkan bahawa proses penjerapan telah dikawal oleh penjerapan kimia. Kelakuan penjerapan telah digambarkan secara baik oleh model isoterma Langmuir dimana q_{max} adalah 588.24 mg/g. Daripada plot pelbagai linear penyebaran intra partikel,

mencadangkan bahawa dua langkah penjerapan telah terlibat dalam penjerapan ion-ion Pb(II). Oleh itu, dalam kajian ini penjerap telah berjaya dihasilkan daripada campuran PAN dan lignin daripada sisa sagu dan PAN/SL ACNFs mempunyai potensi untuk digunakan sebagai penjerap bagi menyingkirkan Pb(II) daripada larutan akues.

ACKNOWLEDGEMENTS

In the name of Allah, The Most Gracious, The Most Merciful.

Praises to Allah The Almighty for giving me the opportunity to pursue my study and for giving me the strength to endure the hardships during my study.

Firstly, I would like to take this opportunity to express my deepest gratitude and appreciation to my supervisor, Dr. Norizah Abdul Rahman and my co-supervisor, Prof. Abdul Halim Abdullah whose guidance, encouragement, and knowledge enable me to develop an understanding throughout the research and discuss regarding any misunderstanding throughout our meeting sessions.

Next, I would like to thank my colleagues for their helps and support during my research and to the staffs from Chemistry Department, Faculty of Science UPM for their assistance. I also would like to thank Malaysian Nuclear Agency for providing the sago waste, Dr. Md Shuhazlly Mamat @ Mat Nazir from Physics Department of Faculty of Sciences UPM and Mrs. Nor Salmi Abdullah from National Hydraulic Research Institute of Malaysia (NAHRIM) for providing the furnace and inert gas for carbonization.

To my beloved family, especially my mother, father, and my older brothers, I always grateful for their moral support and financial support throughout my study.

Lastly, I offer my gratitude to whoever that had supported me in any way in my journey on completing my study.

I certify that a Thesis Examination Committee has met on 4 November 2019 to conduct the final examination of Nurul Aida Nordin on her thesis entitled "Blends of Polyacrylonitrile and Lignin of Sago Waste For Production of Carbon Nanofibers for Removal of Lead(II) From Aqueous Solution" 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.

Members of the Thesis Examination Committee were as follows:

Mohamed Ibrahim bin Mohamed Tahir, PhD
Senior Lecturer
Faculty of Science
Universiti Putra Malaysia
(Chairman)

Tan Yen Ping, PhD
Senior Lecturer
Faculty of Science
Universiti Putra Malaysia
(Internal Examiner)

Rusli bin Daik, PhD
Professor
Faculty of Science and TechnologyNational
University of Malaysia
Malaysia
(External Examiner)

SITI SALWA ABD GANI, PhD
Associate Professor ChM, and Deputy
School of Graduate Studies
Universiti Putra Malaysia

Date: 07 August 2020

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

Norizah Abdul Rahman, PhD
Senior Lecturer
Faculty of Science
Universiti Putra Malaysia
(Chairman)

Abdul Halim Abdullah, PhD
Associate Professor
Faculty of Science
Universiti Putra Malaysia
(Member)

____
ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 13 August 2020

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: ______________________________
Name of Chairman of Supervisory Committee: Dr. Norizah Abdul Rahman

Signature: ______________________________
Name of Member of Supervisory Committee: Associate Professor Dr. Abdul Halim Abdullah

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

AC	Activated carbon
ACNFs	Activated carbon nanofibers
BE	Binding energy
BET	Brunauer-Emmett-Teller
b_L	Langmuir constant
CNFs	Carbon nanofibers
CNTs	Carbon nanotubes
CVD	Chemical vapour deposition
DMF	N-N, dimethylformamide
DSC	Differential Scanning Calorimetry
DTG	Differential Thermal Gravimetric
FTIR	Fourier Transform Infrared
ICP	Inductively Coupled Plasma
IPD	Intra-particle diffusion
k_1	Pseudo-first rate constant
k_2	Pseudo-second rate constant
K_F	Freundlich constant
PAN	Polyacrylonitrile
Pb	Lead (plumbum)
q	Adsorption capacity
R^2	Correlation coefficient
SEM	Scanning Electron Microscopy
TGA	Thermal Gravimetric Analysis
XPS	X-Ray Photoelectron Scanning
XRD	X-Ray Diffraction

CHAPTER 1

INTRODUCTION

1.1 Heavy metals

Heavy metals are considered to be toxic to human and other biological system due to its non-biodegradable and persistent nature, which has become a public health concern (Jiang *et al.*, 2010). The main sources of heavy metal contamination are mostly contributed from metal bearing industries such as industries of batteries, tanneries, electrical, electroplating, fertilizers, pesticides, mining, and refining ores (Baneerje *et al.*, 2012, Nguyen *et al.*, 2013, Yunus *et al.*, 2006).

Heavy metals can contribute to the environmental problems which could have an impact to human due to its toxicity. The heavy metal pollution could bring an implication to the aquatic life bodies, natural water bodies and possibly get trapped in the soil through bioaccumulation (Desta, 2013). Its high solubility in aquatic environment allows it to be absorbed by living organisms and large concentrations of heavy metals might accumulate in human body once they entered our food chain and caused serious health disorder (Barakat, 2011).

Lead has been utilized as industrial raw materials for battery manufacturing, printing, pigments, fuels, photographic materials, and dyeing (Zulkali *et al.*, 2006). Lead is metal which might be at the highest of the environmental concerns (Jalali *et al.*, 2002, Volesky, 1994). A few techniques have been generally developed for removal of lead from wastewater such as electrochemical treatment, ion exchange, coagulation, reverse osmosis, membrane filtration, adsorption, etc. (Quintelas *et al.*, 2009).

Previous study had proved that water treatment by adsorption to be the most convenient, simple, economical, and effective to be used in practical applications (Chen *et al.*, 2013, Wang *et al.*, 2015a). Many adsorbents such as fly ash, kaolinite clay, zeolites, industrial by-products, agricultural waste, polymeric materials and carbon materials had been used in the treatment of wastewater (Barakat, 2011). Carbon-based materials were found to be effective adsorbents for removal of heavy metal due to their well-developed internal pore structures, large specific surface area, and presence of surface functional groups (Pyrzyńska and Bystrzejewski, 2010).

The surface of carbon materials can be transformed into more hydrophilic by introducing oxygen-containing groups which could improves their wettability for polar solvents that can be utilized for the attachments of Pb(II) ions (Dongil *et al.*, 2011). Among various oxidation treatments, nitric acid was considered to be the most conventional and widely used in wet oxidation treatment (Soudani *et al.*, 2013). The presence of oxygen functional groups on surface of carbon adsorbents was investigated for removal of Pb(II) ions from aqueous solution and Pb(II) ions have a tendency to form metal complexes with the negatively-charged oxygen functional groups and the adsorption was found to be highly favorable (Bhatnagar *et al.*, 2013).

1.2 Sago lignin

Sago palm were scientifically known as *Metroxylan sago* and it were originated from the species of palm in the *Metroxylan* genus (Nordin *et al.*, 2018). The stems will develop into a huge frond that was flourished with fruits as it terminates its' life cycle (Orwa *et al.*, 2009). Sago palm will convert its nutrients into starch just before flowering because it exhibit hapaxanthic characteristics in which it will dies shortly once it flowering (Awg-Adeni *et al.*, 2010). One of the physical characteristics of sago palm is its fruits which are not encapsulated or in other words can be said as naked-seed or scientifically termed as gymnosperms. Most gymnosperms are known to be softwood. Sago palm grows well in swampy areas in Sarawak, Malaysia. Ishazaki (2009) reported that approximately 5 to 11 tons of wastes are produced every day from a single sago starch processing mill that contain starchy lignocellulosic by-products. Common products derived from sago palm besides sago starch are the ground pith as the animal feed, the cortex of the trunk used for firing in paper mills and the leaves that can be turned into mats (Orwa *et al.*, 2009).

Previous study stated that natural polymers received massive attention from the researchers in order to reduce the consumption of petroleum-based polymer (Abdel-Halim and Al-Deyab, 2011). Cellulose, starch and lignin are among the natural polymers which possessed interesting characteristics such as biodegradable, non-toxic, and low cost. Lignin is the second most abundant natural polymer after cellulose (Watkins *et al.*, 2015). Sago lignin is renewable and it is readily available from the sago wastes which comprised of lignocellulosic by-products of sago starch extraction process. Lignin plays an important role as to provide the stiffening and rigidity to the plants by holding the fibers together. According to Awg-Adeni *et al.* (2010), lignin is usually linked with the hemicelluloses in the cell walls of sago pith and it is the main component of sago bark.

Lignin is the largest available resource of natural aromatic polymers that composed of three-dimensional and highly crosslinked macromolecule which made up of three types of substituted phenols: coniferyl, sinapyl and p-coumaryl alcohols (Eudes *et al.*, 2014, Okutan *et al.*, 2014, Watkins *et al.*, 2015). The most common lignin sources come from hardwood lignin, softwood lignin and grass lignin. Figure 1.1 shows the schematic representation of the lignin structure. As lignin is strongly associated with hemicelluloses, the extraction process usually started by dissolving the lignin from the wood and followed by isolation process (Chang *et al.*, 2016). Sago lignin has the potential in the production of carbon-based adsorbents owing to its structure which consist of many aromatic components.

In order to reduce the environmental problem due to the used of polyacrylonitrile (PAN), PAN was blended with sago lignin and electrospun, followed by thermal treatment to formed carbon nanofibers (CNFs). In this method, there is no consumption of elemental transition metal catalyst and no significant amount of catalyst residue was left. Therefore, electrospinning method is suitable in producing a free catalyst and high product yield. Besides that, blending is an effective method to improve the ability of sago lignin to be electrospun into nanofibers.

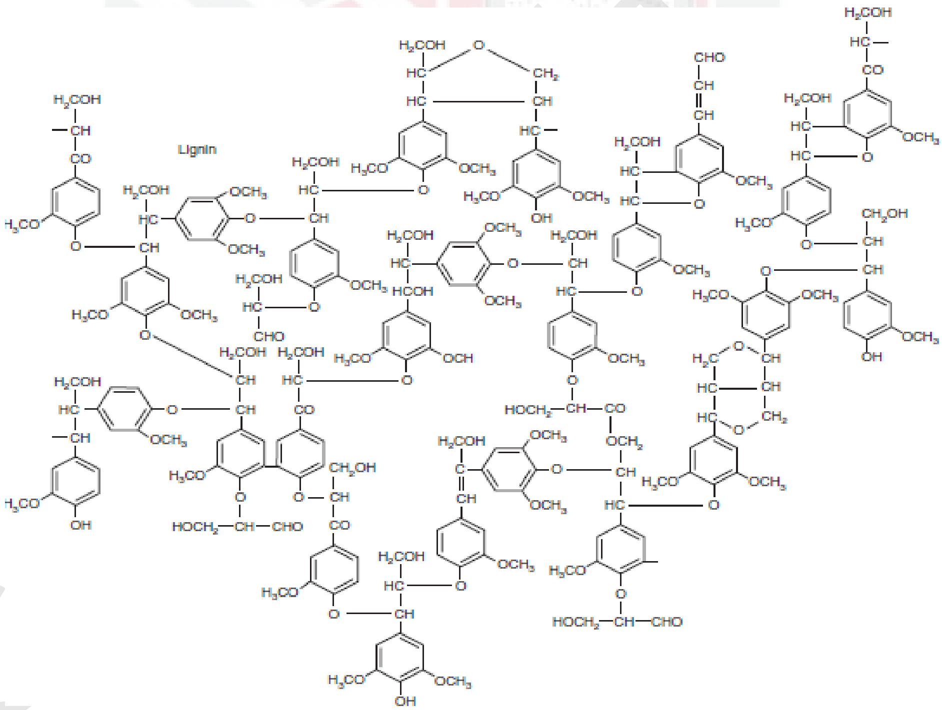

Figure 1.1 : Schematic representation of lignin structure
(Watkins *et al*., 2015)

1.3 Problem statement

Development of adsorbents to remove heavy metal ions is crucial to our present society as heavy metals cannot be destroyed or degraded. In order to reduce human intake of heavy metals both chemical and physical treatment has been investigated and water treatment by adsorption was found to be the most economical and practical treatment alternative (Ihsanullah *et al.*, 2015).

Chemical and thermal stability accompanied with large surface area could make CNFs as a good material to be employed as an adsorbent (Li *et al.*, 2015b). However, common precursors to produce carbon fibers are PAN, cellulose, and pitch (Frank *et al.*, 2012). The most commonly used precursor, PAN was extensively used due to its high carbon yield compared to cellulose and pitch. PAN is petroleum-based material and it is accounted as the precursor for about 95% of carbon fibers manufactured today (Lin *et al.*, 2013). In todays' world, sustainable and renewable resources are overcoming the so-called petroleum-based resources because they are abundant, cheaper and causing less harmful to the environment.

There is an increasing amount of research focusing on the use of waste materials as adsorbents, aligned with the environmental protection awareness. In this study, sago lignin was isolated from sago waste and was blended with PAN. The nanofibers undergo thermal treatment followed by activation by nitric acid to produce activated CNFs. ACNFs was used as the adsorbent because it has high specific surface area and presence of oxygen-functional groups which could enhance the metal uptake by the adsorbent. In this research, the adsorption of Pb(II) ions by CNFs and activated CNFs from aqueous solution was observed. The adsorption of Pb(II) was more effective when CNFs were activated with nitric acid and its kinetic and adsorption isotherm were studied.

1.4 Significance of the study

It was reported that a single sago starch processing mill will create about 7 tons of sago waste every day (Pushpamalar *et al.*, 2006). These waste are usually managed by discharging them into the river which can contribute to the environmental pollution. It is only wise if these waste can be recycled into something beneficial since they contain large amount of lignocellulosic by-products which are cellulose, hemicellulose and lignin. Due to its biodegradability and non-toxicity, it is easier to degrade and safer compared to synthetic polymers.

In addition, lignin was less explored as the precursors to produce CNFs. Lignin has the potential in the production of carbon-based materials due to its structure which consists of many aromatic components. Unlike catalytic synthesis, electrospinning polymer such as PAN followed by thermal treatment has become a simple and straightforward method to make continuous carbon nanofibers (CNFs).

Electrospinning method has many advantages such as simple setup, cheap, easy to control fiber diameter and less time consuming for nanofibers preparation compared to other methods. Electrospinning is a straightforward method that does not require any catalyst which could produce catalyst residue and continuous fibers were easy to formed.

1.5 Objectives of the study

1.5.1 General objective

The objective of this research is to produce ACNFs from blends of PAN and lignin of sago waste as the adsorbent for the removal of Pb(II) ions from aqueous solution.

1.5.2 Specific objectives

1. To prepare and characterize the ACNFs from electrospun PAN/SL preparedby electrospinning.
2. To evaluate the potential of PAN/SL-based ACNFs as adsorbent for Pb(II)ions removal.

REFERENCES

Abdel-Halim, E. S. and Al-Deyab, S. S. (2011) Removal of heavy metals from their aqueous solutions through adsorption onto natural polymers. *Carbohydrate Polymers.* 84**.** 454-458.

Abdelnaeim, M. Y., El Sherif, I. Y., Attia, A. A., Fathy, N. A. and El-Shahat, M. F. (2016) Impact of chemical activation on the adsorption performance of common reed towards Cu(II) and Cd(II). *International Journal of Mineral Processing.* 157**.** 80-88.

Abdelwahab, O., Amin, N. K. and El-Ashtoukhy, E. S. Z. (2013) Removal of zinc ions from aqueous solution using a cation exchange resin. *Chemical Engineering Research and Design.* 91**.** 165-173.

Abeykoon, N. C., Bonso, J. S. and Ferraris, J. P. (2015) Supercapacitor performance of carbon nanofiber electrodes derived from immiscible PAN/PMMA polymer blends. *RSC Advances.* 5**.** 19865-19873.

Ahmad, A., Rafatullah, M., Sulaiman, O., Ibrahim, M. H., Chii, Y. Y. and Siddique, B. M. (2009) Removal of Cu(II) and Pb(II) ions from aqueous solutions by adsorption on sawdust of Meranti wood. *Desalination.* 247**.** 636-646.

Ahmaruzzaman, M. (2011) Industrial wastes as low-cost potential adsorbents for the treatment of wastewater laden with heavy metals. *Advances in Colloid and Interface Science.* 166**.** 36-59.

Ahmed, F. E., Lalia, B. S. and Hashaikeh, R. (2015a) A review on electrospinning for membrane fabrication: Challenges and applications. *Desalination.* 356**.** 15-30.

Ahmed, M. J. K. and Ahmaruzzaman, M. (2016) A review on potential usage of industrial waste materials for binding heavy metal ions from aqueous solutions. *Journal of Water Process Engineering.* 10**.** 39-47.

Ahmed, Y. M., Al-Mamun, A., Al Khatib, M. a. F. R., Jameel, A. T. and Alsaadi, M. a. H. a. R. (2015b) Efficient lead sorption from wastewater by carbon nanofibers. *Environmental Chemistry Letters.* 13**.** 341-346.

Ahuja, D., Kaushik, A. and Singh, M. (2018) Simultaneous extraction of lignin and cellulose nanofibrils from waste jute bags using one pot pre-treatment. *International Journal of Biological Macromolecules.* 107**.** 1294-1301.

Ali, R. M., Hamad, H. A., Hussein, M. M. and Malash, G. F. (2016) Potential of using green adsorbent of heavy metal removal from aqueous solutions: Adsorption kinetics, isotherm, thermodynamic, mechanism and economic analysis. *Ecological Engineering.* 91**.** 317-332.

Alizadeh, B., Ghorbani, M. and Salehi, M. A. (2016) Application of polyrhodanine modified multi-walled carbon nanotubes for high efficiency removal of Pb(II) from aqueous solution. *Journal of Molecular Liquids.* 220**.** 142-149.

Amarasinghe, B. M. W. P. K. and Williams, R. A. (2007) Tea waste as a low cost adsorbent for the removal of Cu and Pb from wastewater. *Chemical Engineering Journal.* 132**.** 299-309.

Araújo, C. S. T., Almeida, I. L. S., Rezende, H. C., Marcionilio, S. M. L. O., Léon, J. J. L. and De Matos, T. N. (2018) Elucidation of mechanism involved in adsorption of Pb(II) onto lobeira fruit (Solanum lycocarpum) using Langmuir, Freundlich and Temkin isotherms. *Microchemical Journal.* 137**.** 348-354.

Arshad, S. N., Naraghi, M. and Chasiotis, I. (2011) Strong carbon nanofibers from electrospun polyacrylonitrile. *Carbon.* 49**.** 1710-1719.

Atieh, M. A. (2011) Effect of functionalized carbon nanofibers with carboxylic functional group on the removal of zinc from water. *International Journal of Environmental Science and Development.* 2**.** 4.

Awg-Adeni, D. S., Abd-Aziz, S., Bujang, K. and Hassan, M. A. (2010) Bioconversion of sago residue into value added products. *African Journal of Biotechnology.* 9**.** 5.

Baker, D. A. and Rials, T. G. (2013) Recent advances in low-cost carbon fiber manufacture from lignin. *Journal of Applied Polymer Science.* 130**.** 713-728.

Baneerje, K., Ramesh, S. T., Gandhimathi, R., Nidheesh, P. V. and Bharathi, K. S. (2012) A novel agriculture waste adsorbent, watermelon shell for the removal of copper from aqueous solutions. *Iranica Journal of Energy & Environment.* 3**.** 13.

Barakat, M. A. (2011) New trends in removing heavy metals from industrial wastewater. *Arabian Journal of Chemistry.* 4**.** 361-377.

Beck, R. J., Zhao, Y., Fong, H. and Menkhaus, T. J. (2017) Electrospun lignin carbon nanofiber membranes with large pores for highly efficient adsorptive water treatment applications. *Journal of Water Process Engineering.* 16**.** 240-248.

Bernard, E., Jimoh, A. and Odigure, J. O. (2013) Heavy metals removal from industrial wastewater by activated carbon prepared from coconut shell. *Research Journal of Chemical Sciences.* 3**.** 3-9.

Bhardwaj, N. and Kundu, S. C. (2010) Electrospinning: A fascinating fiber fabrication technique. *Biotechnology Advances.* 28**.** 325-347.

Bhatnagar, A., Hogland, W., Marques, M. and Sillanpää, M. (2013) An overview of the modification methods of activated carbon for its water treatment applications. *Chemical Engineering Journal.* 219**.** 499-511.

Boikanyo, D., Masheane, M. L., Nthunya, L. N., Mishra, S. B. and Mhlanga, S.D. (2018) 5 - Carbon-supported photocatalysts for organic dye photodegradation. IN HUSSAIN, C. M. & MISHRA, A. K. (Eds.) *New Polymer Nanocomposites for Environmental Remediation.* Elsevier.

Bouhamed, F., Elouear, Z. and Bouzid, J. (2012) Adsorptive removal of copper(II) from aqueous solutions on activated carbon prepared from Tunisian date stones: Equilibrium, kinetics and thermodynamics. *Journal of the Taiwan Institute of Chemical Engineers.* 43**.** 741-749.

Cao, J., Xiao, G., Xu, X., Shen, D. and Jin, B. (2013) Study on carbonization of lignin by TG-FTIR and high-temperature carbonization reactor. *Fuel Processing Technology.* 106**.** 41-47.

Celebioglu, A. and Uyar, T. (2011) Electrospun porous cellulose acetate fibers from volatile solvent mixture. *Materials Letters.* 65**.** 2291-2294.

Chakraborty, A., Deva, D., Sharma, A. and Verma, N. (2011) Adsorbents based on carbon microfibers and carbon nanofibers for the removal of phenol and lead from water. *Journal of Colloid and Interface Science.* 359**.** 228-239.

Chakrapani, N., Zhang, Y. M., Nayak, S. K., Moore, J. A., Carroll, D. L., Choi, Y. Y. and Ajayan, P. M. (2003) Chemisorption of Acetone on Carbon Nanotubes. *The Journal of Physical Chemistry B.* 107**.** 9308-9311.

Chang, Z.-Z., Yu, B.-J. and Wang, C.-Y. (2016) Lignin-derived hierarchical porous carbon for high-performance supercapacitors. *Journal of Solid State Electrochemistry.* 20**.** 7.

Chaúque, E. F. C., Dlamini, L. N., Adelodun, A. A., Greyling, C. J. and Catherine Ngila, J. (2016) Modification of electrospun polyacrylonitrile nanofibers with EDTA for the removal of Cd and Cr ions from water effluents. *Applied Surface Science.* 369**.** 19-28.

Che Ismail, N. A. (2016) Preparation and Characterizations of Lignin-based Nanofibers From Sago Waste. *Chemistry Department.* Faculty of Science, Universiti Putra Malaysia.

Chen, J.-H., Hsu, K.-C. and Chang, Y.-M. (2013) Surface Modification of Hydrophobic Resin with Tricaprylmethylammonium Chloride for the Removal of Trace Hexavalent Chromium. *Industrial & Engineering Chemistry Research.* 52**.** 11685-11694.

Chen, T., Zhou, Z., Han, R., Meng, R., Wang, H. and Lu, W. (2015) Adsorption of cadmium by biochar derived from municipal sewage sludge: Impact factors and adsorption mechanism. *Chemosphere.* 134**.** 286-293.

Chen, Y., Guo, J. and Kim, H. (2010) Preparation of poly(vinylidene fluoride)/phosphotungstic acid composite nanofiber membranes by electrospinning for proton conductivity. *Reactive and Functional Polymers.* 70**.** 69-74.

Cheng, S. Y., Show, P.-L., Lau, B. F., Chang, J.-S. and Ling, T. C. (2019) New Prospects for Modified Algae in Heavy Metal Adsorption. *Trends in Biotechnology.* 37**.** 1255-1268.

Cho, H., Oh, D. and Kim, K. (2005) A study on removal characteristics of heavy metals from aqueous solution by fly ash. *Journal of Hazardous Materials.* 127**.** 187-195.

Choma, J., Burakiewicz-Mortka, W., Jaroniec, M., Li, Z. and Klinik, J. (1999) Monitoring Changes in Surface and Structural Properties of Porous Carbons Modified by Different Oxidizing Agents. *Journal of Colloid and Interface Science.* 214**.** 438-446.

Dadvar, S., Tavanai, H., Morshed, M. and Ghiaci, M. (2013) A study on the kinetics of 2-chloroethyl ethyl sulfide adsorption onto nanocomposite activated carbon nanofibers containing metal oxide nanoparticles. *Separation and Purification Technology.* 114**.** 24-30.

Dehghani, M. H., Sanaei, D., Ali, I. and Bhatnagar, A. (2016) Removal of chromium(VI) from aqueous solution using treated waste newspaper as a low-cost adsorbent: Kinetic modeling and isotherm studies. *Journal of Molecular Liquids.* 215**.** 671-679.

Desta, M. B. (2013) Batch Sorption Experiments: Langmuir and Freundlich Isotherm Studies for the Adsorption of Textile Metal Ions onto Teff Straw (Eragrostis tef) Agricultural Waste. *Journal of Thermodynamics.* 2013**.** 6.

Dong, L., Liu, W., Jiang, R. and Wang, Z. (2016) Study on the adsorption mechanism of activated carbon removing low concentrations of heavy metals. *Desalination and Water Treatment.* 57**.** 7812-7822.

Dongil, A. B., Bachiller-Baeza, B., Guerrero-Ruiz, A., Rodríguez-Ramos, I., Martínez-Alonso, A. and Tascón, J. M. D. (2011) Surface chemical modifications induced on high surface area graphite and carbon nanofibers using different oxidation and functionalization treatments. *Journal of Colloid and Interface Science.* 355**.** 179-189.

Dwivedi, C. P., Sahu, J. N., Mohanty, C. R., Mohan, B. R. and Meikap, B. C. (2008) Column performance of granular activated carbon packed bed for Pb(II) removal. *Journal of Hazardous Materials.* 156**.** 596-603.

El-Ashtoukhy, E. S. Z., Amin, N. K. and Abdelwahab, O. (2008) Removal of lead (II) and copper (II) from aqueous solution using pomegranate peel as a new adsorbent. *Desalination.* 223**.** 162-173.

El-Hendawy, A.-N. A. (2003) Influence of HNO_3 oxidation on the structure and adsorptive properties of corncob-based activated carbon. *Carbon.* 41**.** 713-722.

Eudes, A., Liang, Y., Mitra, P. and Loqué, D. (2014) Lignin bioengineering. *Current Opinion in Biotechnology.* 26**.** 189-198.

Faccini, M., Borja, G., Boerrigter, M., Mart, M., #Xed, N, D., Mart, #Xec, Nez Crespiera, S., #Xe1, Zquez-Campos, S., Aubouy, L. and Amantia, D. (2015) Electrospun Carbon Nanofiber Membranes for Filtration of Nanoparticles from Water. *Journal of Nanomaterials.* 2015**.** 9.

Faghihian, H., Kooravand, M. and Atarodi, H. (2012) Synthesis of a novel carbon nanofiber structure for removal of lead. *Korean Journal of Chemical Engineering.* 30**.** 357-363.

Farooq, U., Kozinski, J. A., Khan, M. A. and Athar, M. (2010) Biosorption of heavy metal ions using wheat based biosorbents – A review of the recent literature. *Bioresource Technology.* 101**.** 5043-5053.

Feizi, M. and Jalali, M. (2015) Removal of heavy metals from aqueous solutions using sunflower, potato, canola and walnut shell residues. *Journal of the Taiwan Institute of Chemical Engineers.* 54**.** 125-136.

Frank, E., Hermanutz, F. and Buchmeiser, M. R. (2012) Carbon Fibers: Precursors, Manufacturing, and Properties. *Macromolecular Materials and Engineering.* 297**.** 493-501.

Fu, F. and Wang, Q. (2011) Removal of heavy metal ions from wastewaters: A review. *Journal of Environmental Management.* 92**.** 407-418.

Fu, L., Mccallum, S. A., Miao, J., Hart, C., Tudryn, G. J., Zhang, F. and Linhardt, R. J. (2015) Rapid and accurate determination of the lignin content of lignocellulosic biomass by solid-state NMR. *Fuel.* 141**.** 39-45.

Gao, J.-J., Qin, Y.-B., Zhou, T., Cao, D.-D., Xu, P., Hochstetter, D. and Wang, Y.-F. (2013) Adsorption of methylene blue onto activated carbon produced from tea (Camellia sinensis L.) seed shells: kinetics, equilibrium, and thermodynamics studies. *Journal of Zhejiang University. Science. B.* 14**.** 650-658.

Gokce, Y. and Aktas, Z. (2014) Nitric acid modification of activated carbon produced from waste tea and adsorption of methylene blue and phenol. *Applied Surface Science.* 313**.** 352-359.

Guo, Z., Zhou, D., Liu, H., Dong, X., Yuan, S., Yu, A., Wang, Y. and Xia, Y. (2015) Synthesis of ruthenium oxide coated ordered mesoporous carbon nanofiber arrays as a catalyst for lithium oxygen battery. *Journal of Power Sources.* 276**.** 181-188.

Gupta, V. K., Agarwal, S., Bharti, A. K. and Sadegh, H. (2017) Adsorption mechanism of functionalized multi-walled carbon nanotubes for advanced Cu (II) removal. *Journal of Molecular Liquids.* 230**.** 667-673.

Gupta, V. K., Agarwal, S. and Saleh, T. A. (2011) Synthesis and characterization of alumina-coated carbon nanotubes and their application for lead removal. *Journal of Hazardous Materials.* 185**.** 17-23.

Gupta, V. K., Moradi, O., Tyagi, I., Agarwal, S., Sadegh, H., Shahryari-Ghoshekandi, R., Makhlouf, A. S. H., Goodarzi, M. and Garshasbi, A. (2016) Study on the removal of heavy metal ions from industry waste by carbon nanotubes: Effect of the surface modification: a review. *Critical Reviews in Environmental Science and Technology.* 46**.** 93-118.

Hajdu, I., Bodnár, M., Csikós, Z., Wei, S., Daróczi, L., Kovács, B., Győri, Z., Tamás, J. and Borbély, J. (2012) Combined nano-membrane technology for removal of lead ions. *Journal of Membrane Science.* 409-410**.** 44-53.

Igura, M. and Okazaki, M. (2010) Cadmium sorption characteristics of phosphorylated sago starch-extraction residue. *Journal of Hazardous Materials.* 178**.** 686-692.

Ihsanullah, Al-Khaldi, F. A., Abusharkh, B., Khaled, M., Atieh, M. A., Nasser, M. S., Laoui, T., Saleh, T. A., Agarwal, S., Tyagi, I. and Gupta, V. K. (2015) Adsorptive removal of cadmium(II) ions from liquid phase using acid modified carbon-based adsorbents. *Journal of Molecular Liquids.* 204**.** 255-263.

Inagaki, M., Toyoda, M., Soneda, Y. and Morishita, T. (2018) Nitrogen-doped carbon materials. *Carbon.* 132**.** 104-140.

Inagaki, M., Yang, Y. and Kang, F. (2012) Carbon Nanofibers Prepared via Electrospinning. *Advanced Materials.* 24**.** 2547-2566.

Ishazaki, A. (2009) Sago, an attractive renewable resource which saves human's crisis of environment and energy. 3.

Jacobs, V., Anandjiwala, R. D. and Maaza, M. (2010) The influence of electrospinning parameters on the structural morphology and diameter of electrospun nanofibers. *Journal of Applied Polymer Science.* 115**.** 3130-3136.

Jalali, R., Ghafourian, H., Asef, Y., Davarpanah, S. J. and Sepehr, S. (2002) Removal and recovery of lead using nonliving biomass of marine algae. *Journal of Hazardous Materials.* 92**.** 253-262.

Ji, L., Yao, Y., Toprakci, O., Lin, Z., Liang, Y., Shi, Q., Medford, A. J., Millns, C. R. and Zhang, X. (2010) Fabrication of carbon nanofiber-driven electrodes from electrospun polyacrylonitrile/polypyrrole bicomponents for high-performance rechargeable lithium-ion batteries. *Journal of Power Sources.* 195**.** 2050-2056.

Jia, Y. F. and Thomas, K. M. (2000) Adsorption of Cadmium Ions on Oxygen Surface Sites in Activated Carbon. *Langmuir.* 16**.** 1114-1122.

Jiang, M.-Q., Jin, X.-Y., Lu, X.-Q. and Chen, Z.-L. (2010) Adsorption of Pb(II), Cd(II), Ni(II) and Cu(II) onto natural kaolinite clay. *Desalination.* 252**.** 33-39.

Jiang, S., Huang, L., Nguyen, T. a. H., Ok, Y. S., Rudolph, V., Yang, H. and Zhang, D. (2016) Copper and zinc adsorption by softwood and hardwood biochars under elevated sulphate-induced salinity and acidic pH conditions. *Chemosphere.* 142**.** 64-71.

Jin, J., Yu, B.-J., Shi, Z.-Q., Wang, C.-Y. and Chong, C.-B. (2014) Lignin-based electrospun carbon nanofibrous webs as free-standing and binder-free electrodes for sodium ion batteries. *Journal of Power Sources.* 272**.** 800-807.

Ju, J., Kang, W., Deng, N., Li, L., Zhao, Y., Ma, X., Fan, L. and Cheng, B. (2017) Preparation and characterization of PVA-based carbon nanofibers with honeycomb-like porous structure via electro-blown spinning method. *Microporous and Mesoporous Materials.* 239**.** 416-425.

Ju, Y.-W. and Oh, G.-Y. (2017) Behavior of toluene adsorption on activated carbon nanofibers prepared by electrospinning of a polyacrylonitrile-cellulose acetate blending solution. *Korean Journal of Chemical Engineering.* 34**.** 2731-2737.

Kalagasidis Krušić, M., Milosavljević, N., Debeljković, A., Üzüm, Ö. B. and Karadağ, E. (2012) Removal of Pb2+ Ions from Water by Poly(Acrylamide-co-Sodium Methacrylate) Hydrogels. *Water, Air, & Soil Pollution.* 223**.** 4355-4368.

Kang, S., Xiao, L., Meng, L., Zhang, X. and Sun, R. (2012) Isolation and Structural Characterization of Lignin from Cotton Stalk Treated in an Ammonia Hydrothermal System. *International Journal of Molecular Sciences.* 13.

Karacan, I. and Erdoğan, G. (2012) The role of thermal stabilization on the structure and mechanical properties of polyacrylonitrile precursor fibers. *Fibers and Polymers.* 13**.** 855-863.

Keyser, M. M. and Prinsloo, F. F. (2007) Loading of Cobalt on Carbon Nanofibers. IN DAVIS, B. H. & OCCELLI, M. L. (Eds.) *Studies in Surface Science and Catalysis.* Elsevier.

Ko, F. K., Goudarzi, A., Lin, L.-T., Li, Y. and Kadla, J. F. (2016) 9 - Lignin-Based Composite Carbon Nanofibers. IN FARUK, O. & SAIN, M. (Eds.) *Lignin in Polymer Composites.* William Andrew Publishing.

Kołodyńska, D., Krukowska, J. and Thomas, P. (2017) Comparison of sorption and desorption studies of heavy metal ions from biochar and commercial active carbon. *Chemical Engineering Journal.* 307**.** 353-363.

Koukouzas, N., Vasilatos, C., Itskos, G., Mitsis, I. and Moutsatsou, A. (2010) Removal of heavy metals from wastewater using CFB-coal fly ash zeolitic materials. *Journal of Hazardous Materials.* 173**.** 581-588.

Kumar, D. and Gaur, J. P. (2011) Chemical reaction- and particle diffusion-based kinetic modeling of metal biosorption by a Phormidium sp.-dominated cyanobacterial mat. *Bioresource Technology.* 102**.** 633-640.

Kumari, S. and Chauhan, G. S. (2014) New Cellulose–Lysine Schiff-Base-Based Sensor–Adsorbent for Mercury Ions. *ACS Applied Materials & Interfaces.* 6**.** 5908-5917.

Kuzmenko, V., Naboka, O., Gatenholm, P. and Enoksson, P. (2014) Ammonium chloride promoted synthesis of carbon nanofibers from electrospun cellulose acetate. *Carbon.* 67**.** 694-703.

Lai, C., Zhou, Z., Zhang, L., Wang, X., Zhou, Q., Zhao, Y., Wang, Y., Wu, X.-F., Zhu, Z. and Fong, H. (2014) Free-standing and mechanically flexible mats consisting of electrospun carbon nanofibers made from a natural product of alkali lignin as binder-free electrodes for high-performance supercapacitors. *Journal of Power Sources.* 247**.** 134-141.

Lai, J. C., Rahman, W. a. W. A. and Toh, W. Y. (2013) Characterisation of sago pith waste and its composites. *Industrial Crops and Products.* 45**.** 319-326.

Lee, K. J., Shiratori, N., Lee, G. H., Miyawaki, J., Mochida, I., Yoon, S.-H. and Jang, J. (2010) Activated carbon nanofiber produced from electrospun polyacrylonitrile nanofiber as a highly efficient formaldehyde adsorbent. *Carbon.* 48**.** 4248-4255.

León, G., García, F., Miguel, B. and Bayo, J. (2016) Equilibrium, kinetic and thermodynamic studies of methyl orange removal by adsorption onto granular activated carbon. *Desalination and Water Treatment.* 57**.** 17104-17117.

Li, J. (2011) Isolation of lignin from wood. *Unit of Technology.* Imatra, Bachelor's Thesis, Saimaa University of Applied Sciences.

Li, L., Li, Y., Cao, L. and Yang, C. (2015a) Enhanced chromium (VI) adsorption using nanosized chitosan fibers tailored by electrospinning. *Carbohydrate Polymers.* 125**.** 206-213.

Li, X., Chen, S., Fan, X., Quan, X., Tan, F., Zhang, Y. and Gao, J. (2015b) Adsorption of ciprofloxacin, bisphenol and 2-chlorophenol on electrospun carbon nanofibers: In comparison with powder activated carbon. *Journal of Colloid and Interface Science.* 447**.** 120-127.

Lin, L., Yingjie, L. and Frank, K. K. (2013) Fabrication and Properties of Lignin Based Carbon Nanofiber. *Journal of Fiber Bioengineering and Informatics.* 6**.** 12.

Liu, H. C., Chien, A.-T., Newcomb, B. A., Bakhtiary Davijani, A. A. and Kumar, S. (2016) Stabilization kinetics of gel spun polyacrylonitrile/lignin blend fiber. *Carbon.* 101**.** 382-389.

Liu, Y., Park, M., Ding, B., Kim, J., El-Newehy, M., Al-Deyab, S. S. and Kim, H.-Y. (2015) Facile electrospun Polyacrylonitrile/poly(acrylic acid) nanofibrous membranes for high efficiency particulate air filtration. *Fibers and Polymers.* 16**.** 629-633.

Luo, W., Schardt, J., Bommier, C., Wang, B., Razink, J., Simonsen, J. and Ji, X. (2013) Carbon nanofibers derived from cellulose nanofibers as a long-life anode material for rechargeable sodium-ion batteries. *Journal of Materials Chemistry A.* 1**.** 10662-10666.

Lv, D., Liu, Y., Zhou, J., Yang, K., Lou, Z., Baig, S. A. and Xu, X. (2018) Application of EDTA-functionalized bamboo activated carbon (BAC) for Pb(II) and Cu(II) removal from aqueous solutions. *Applied Surface Science.* 428**.** 648-658.

Ma, C., Song, Y., Shi, J., Zhang, D., Zhong, M., Guo, Q. and Liu, L. (2012) Phenolic-based carbon nanofiber webs prepared by electrospinning for supercapacitors. *Materials Letters.* 76**.** 211-214.

Maaloul, N., Oulego, P., Rendueles, M., Ghorbal, A. and Díaz, M. (2017) Novel biosorbents from almond shells: Characterization and adsorption properties modeling for Cu(II) ions from aqueous solutions. *Journal of Environmental Chemical Engineering.* 5**.** 2944-2954.

Maddah, B., Soltaninezhad, M., Adib, K. and Hasanzadeh, M. (2017) Activated carbon nanofiber produced from electrospun PAN nanofiber as a solid phase extraction sorbent for the preconcentration of organophosphorus pesticides. *Separation Science and Technology.* 52**.** 700-711.

Malekbala, M. R., Khan, M. A., Hosseini, S., Abdullah, L. C. and Choong, T. S. Y. (2015) Adsorption/desorption of cationic dye on surfactant modified mesoporous carbon coated monolith: Equilibrium, kinetic and thermodynamic studies. *Journal of Industrial and Engineering Chemistry.* 21**.** 369-377.

Mamun, A. A., Ahmed, Y. M., Muyibi, S. A., Al-Khatib, M. F. R., Jameel, A. T. and Alsaadi, M. A. (2016) Synthesis of carbon nanofibers on impregnated powdered activated carbon as cheap substrate. *Arabian Journal of Chemistry.* 9**.** 532-536.

Mansour, M. S., Ossman, M. E. and Farag, H. A. (2011) Removal of Cd (II) ion from waste water by adsorption onto polyaniline coated on sawdust. *Desalination.* 272**.** 301-305.

Martin-Gullon, I., Vera, J., Conesa, J. A., González, J. L. and Merino, C. (2006) Differences between carbon nanofibers produced using Fe and Ni catalysts in a floating catalyst reactor. *Carbon.* 44**.** 1572-1580.

Mohd, A. M. D., Islam, M. N. and Noor, B. M. (2001) Enzymic Extraction of Native Starch from Sago (Metroxylon sagu) Waste Residue. *Starch - Stärke.* 53**.** 639-643.

Momčilović, M., Purenović, M., Bojić, A., Zarubica, A. and Ranđelović, M. (2011) Removal of lead(II) ions from aqueous solutions by adsorption onto pine cone activated carbon. *Desalination.* 276**.** 53-59.

Monisha, J., Tenzin, T., Naresh, A., Blessy, B. M. and Krishnamurthy, N. B. (2014) Toxicity, mechanism and health effects of some heavy metals. *Interdisciplinary Toxicology.* 7**.** 60-72.

Monteil-Rivera, F., Phuong, M., Ye, M., Halasz, A. and Hawari, J. (2013) Isolation and characterization of herbaceous lignins for applications in biomaterials. *Industrial Crops and Products.* 41**.** 356-364.

Mouni, L., Merabet, D., Bouzaza, A. and Belkhiri, L. (2011) Adsorption of Pb(II) from aqueous solutions using activated carbon developed from Apricot stone. *Desalination.* 276**.** 148-153.

Nadji, H., Diouf, P. N., Benaboura, A., Bedard, Y., Riedl, B. and Stevanovic, T. (2009) Comparative study of lignins isolated from Alfa grass (Stipa tenacissima L.). *Bioresource Technology.* 100**.** 3585-3592.

Neghlani, P. K., Rafizadeh, M. and Taromi, F. A. (2011) Preparation of aminated-polyacrylonitrile nanofiber membranes for the adsorption of metal ions: Comparison with microfibers. *Journal of Hazardous Materials.* 186**.** 182-189.

Nguyen, T. A. H., Ngo, H. H., Guo, W. S., Zhang, J., Liang, S., Yue, Q. Y., Li, Q. and Nguyen, T. V. (2013) Applicability of agricultural waste and by-products for adsorptive removal of heavy metals from wastewater. *Bioresource Technology.* 148**.** 574-585.

Nordin, N. A., Rahman, N. A., Talip, N. and Yacob, N. (2018) Citric Acid Cross-Linking of Carboxymethyl Sago Starch Based Hydrogel for Controlled Release Application. *Macromolecular Symposia.* 382**.** 1800086.

Nyamukamba, P., Okoh, O., Tichagwa, L. and Greyling, C. (2016) Preparation of Titanium Dioxide Nanoparticles Immobilized on Polyacrylonitrile Nanofibres for the Photodegradation of Methyl Orange. *International Journal of Photoenergy.* 2016**.** 9.

Oh, G.-Y., Ju, Y.-W., Kim, M.-Y., Jung, H.-R., Kim, H. J. and Lee, W.-J. (2008) Adsorption of toluene on carbon nanofibers prepared by electrospinning.*Science of The Total Environment.* 393**.** 341-347.

Okutan, N., Terzi, P. and Altay, F. (2014) Affecting parameters on electrospinning process and characterization of electrospun gelatin nanofibers. *Food Hydrocolloids.* 39**.** 19-26.

Ono, H. and Oya, A. (2006) Preparation of highly crystalline carbon nanofibers from pitch/polymer blend. *Carbon.* 44**.** 682-686.

Orwa, C., Mutua, A., Kindt, R., Jamnadass, R. and Anthony, S. (2009) Agroforestree Database: a tree reference and selection guide version 4.0.

Ouyang, Q., Cheng, L., Wang, H. and Li, K. (2008) Mechanism and kinetics of the stabilization reactions of itaconic acid-modified polyacrylonitrile. *Polymer Degradation and Stability.* 93**.** 1415-1421.

Pang, F. M., Kumar, P., Teng, T. T., Mohd Omar, A. K. and Wasewar, K. L. (2011) Removal of lead, zinc and iron by coagulation–flocculation. *Journal of the Taiwan Institute of Chemical Engineers.* 42**.** 809-815.

Pathania, D., Sharma, S. and Singh, P. (2017) Removal of methylene blue by adsorption onto activated carbon developed from Ficus carica bast. *Arabian Journal of Chemistry.* 10**.** S1445-S1451.

Pimolpun, K. and Pitt, S. (2014) The Study of Competitive Adsorption of Heavy Metal Ions from Aqueous Solution by Aminated Polyacrylonitrile Nanofiber Mats. *Energy Procedia.* 56**.** 142-151.

Poveda, R. L. and Gupta, N. (2016) Carbon Nanofibers: Structure and Fabrication. *Carbon Nanofiber Reinforced Polymer Composites.* Cham. Springer International Publishing.

Pushpamalar, V., Langford, S. J., Ahmad, M. and Lim, Y. Y. (2006) Optimization of reaction conditions for preparing carboxymethyl cellulose from sago waste. *Carbohydrate Polymers.* 64**.** 312-318.

Pyrzyńska, K. and Bystrzejewski, M. (2010) Comparative study of heavy metal ions sorption onto activated carbon, carbon nanotubes, and carbon-encapsulated magnetic nanoparticles. *Colloids and Surfaces A: Physicochemical and Engineering Aspects.* 362**.** 102-109.

Quintelas, C., Rocha, Z., Silva, B., Fonseca, B., Figueiredo, H. and Tavares, T. (2009) Removal of Cd(II), Cr(VI), Fe(III) and Ni(II) from aqueous solutions by an E. coli biofilm supported on kaolin. *Chemical Engineering Journal.* 149**.** 319-324.

Rahaman, M. S. A., Ismail, A. F. and Mustafa, A. (2007) A review of heat treatment on polyacrylonitrile fiber. *Polymer Degradation and Stability.* 92**.** 1421-1432.

Rais, D. and Zibek, S. (2019) Biotechnological and Biochemical Utilization of Lignin. IN WAGEMANN, K. & TIPPKÖTTER, N. (Eds.) *Biorefineries.* Cham. Springer International Publishing.

Rajzer, I., Kwiatkowski, R., Piekarczyk, W., Biniaś, W. and Janicki, J. (2012) Carbon nanofibers produced from modified electrospun PAN/hydroxyapatite precursors as scaffolds for bone tissue engineering. *Materials Science and Engineering: C.* 32**.** 2562-2569.

Ruiz-Rosas, R., Bedia, J., Lallave, M., Loscertales, I. G., Barrero, A., Rodríguez-Mirasol, J. and Cordero, T. (2010) The production of submicron diameter carbon fibers by the electrospinning of lignin. *Carbon.* 48**.** 696-705.

Saeed, K., Haider, S., Oh, T.-J. and Park, S.-Y. (2008) Preparation of amidoxime-modified polyacrylonitrile (PAN-oxime) nanofibers and their applications to metal ions adsorption. *Journal of Membrane Science.* 322**.** 400-405.

Schwanninger, M. and Hinterstoisser, B. (2002) Klason Lignin: Modifications to Improve the Precision of the Standardized Determination. *Holzforschung.*

Seo, D. K., Jeun, J. P., Kim, H. B. and Kang, P. H. (2011) Preparation and characterization of the carbon nanofiber mat produced from electrospun PAN/Lignin precursors by electron beam irradiation. *Reviews on Advanced Materials Science.* 28**.** 4.

Shamsijazeyi, H. and Kaghazchi, T. (2010) Investigation of nitric acid treatment of activated carbon for enhanced aqueous mercury removal. *Journal of Industrial and Engineering Chemistry.* 16**.** 852-858.

Shen, D. K., Gu, S., Luo, K. H., Wang, S. R. and Fang, M. X. (2010) The pyrolytic degradation of wood-derived lignin from pulping process. *Bioresource Technology.* 101**.** 6136-6146.

Shi, G., Liu, C., Wang, G., Chen, X., Li, L., Jiang, X., Zhang, P., Dong, Y., Jia, S., Tian, H., Liu, Y., Wang, Z., Zhang, Q. and Zhang, H. (2019) Preparation and electrochemical performance of electrospun biomass-based activated carbon nanofibers. *Ionics.* 25**.** 1805-1812.

Shim, J.-W., Park, S.-J. and Ryu, S.-K. (2001) Effect of modification with HNO3 and NaOH on metal adsorption by pitch-based activated carbon fibers. *Carbon.* 39**.** 1635-1642.

Shokrollahzadeh, S. and Tajik, S. (2018) Fabrication of thin film composite forward osmosis membrane using electrospun polysulfone/polyacrylonitrile blend nanofibers as porous substrate. *Desalination.* 425**.** 68-76.

Singhal, R. S., Kennedy, J. F., Gopalakrishnan, S. M., Kaczmarek, A., Knill, C. J. and Akmar, P. F. (2008) Industrial production, processing, and utilization of sago palm-derived products. *Carbohydrate Polymers.* 72**.** 1-20.

Song, X., Liu, H., Cheng, L. and Qu, Y. (2010) Surface modification of coconut-based activated carbon by liquid-phase oxidation and its effects on lead ion adsorption. *Desalination.* 255**.** 78-83.

Soudani, N., Souissi-Najar, S. and Ouederni, A. (2013) Influence of Nitric Acid Concentration on Characteristics of Olive Stone Based Activated Carbon. *Chinese Journal of Chemical Engineering.* 21**.** 1425-1430.

Souza De Miranda, C., Ferreira, M. S., Magalhães, M. T., Gonçalves, A. P. B., Carneiro De Oliveira, J., Guimarães, D. H. and José, N. M. (2015) Effect of the Glycerol and Lignin Extracted from Piassava Fiber in Cassava and Corn Starch Films. *Materials Research.* 18**.** 260-264.

Stewart, D. (2008) Lignin as a base material for materials applications: Chemistry, application and economics. *Industrial Crops and Products.* 27**.** 202-207.

Swiatkowski, A., Pakula, M., Biniak, S. and Walczyk, M. (2004) Influence of the surface chemistry of modified activated carbon on its electrochemical behaviour in the presence of lead(II) ions. *Carbon.* 42**.** 3057-3069.

Tan, I. A. W., Hameed, B. H. and Ahmad, A. L. (2007) Equilibrium and kinetic studies on basic dye adsorption by oil palm fibre activated carbon. *Chemical Engineering Journal.* 127**.** 111-119.

Tao, H.-C., Zhang, H.-R., Li, J.-B. and Ding, W.-Y. (2015) Biomass based activated carbon obtained from sludge and sugarcane bagasse for removing lead ion from wastewater. *Bioresource Technology.* 192**.** 611-617.

Teng, M., Qiao, J., Li, F. and Bera, P. K. (2012) Electrospun mesoporous carbon nanofibers produced from phenolic resin and their use in the adsorption of large dye molecules. *Carbon.* 50**.** 2877-2886.

Thamer, B. M., El-Hamshary, H., Al-Deyab, S. S. and El-Newehy, M. H. (2019) Functionalized electrospun carbon nanofibers for removal of cationic dye. *Arabian Journal of Chemistry.* 12**.** 747-759.

Thunga, M., Chen, K., Grewell, D. and Kessler, M. R. (2014) Bio-renewable precursor fibers from lignin/polylactide blends for conversion to carbon fibers. *Carbon.* 68**.** 159-166.

Tytla, M. (2019) Assessment of Heavy Metal Pollution and Potential Ecological Risk in Sewage Sludge from Municipal Wastewater Treatment Plant Located in the Most Industrialized Region in Poland-Case Study. *Int J Environ Res Public Health.* 16.

Uddin, M. K. (2017) A review on the adsorption of heavy metals by clay minerals, with special focus on the past decade. *Chemical Engineering Journal.* 308**.** 438-462.

Vikineswary, S., Shim, Y. L., Thambirajah, J. J. and Blakebrough, N. (1994) Possible microbial utilization of sago processing wastes. *Resources, Conservation and Recycling.* 11**.** 289-296.

Volesky, B. (1994) Advances in biosorption of metals: Selection of biomass types. *FEMS Microbiology Reviews.* 14**.** 291-302.

Wang, F., Lu, X. and Li, X.-Y. (2016) Selective removals of heavy metals (Pb^{2+}, Cu^{2+}, and Cd^{2+}) from wastewater by gelation with alginate for effective metal recovery. *Journal of Hazardous Materials.* 308**.** 75-83.

Wang, M., Leitch, M. and Xu, C. (2009) Synthesis of phenol–formaldehyde resol resins using organosolv pine lignins. *European Polymer Journal.* 45**.** 3380-3388.

Wang, P., Du, M., Zhu, H., Bao, S., Yang, T. and Zou, M. (2015a) Structure regulation of silica nanotubes and their adsorption behaviors for heavy metal ions: pH effect, kinetics, isotherms and mechanism. *Journal of Hazardous Materials.* 286**.** 533-544.

Wang, S. and Peng, Y. (2010) Natural zeolites as effective adsorbents in water and wastewater treatment. *Chemical Engineering Journal.* 156**.** 11-24.

Wang, S., Ru, B., Lin, H., Sun, W. and Luo, Z. (2015b) Pyrolysis behaviors of four lignin polymers isolated from the same pine wood. *Bioresource Technology.* 182**.** 120-127.

Wang, Z., Qie, L., Yuan, L., Zhang, W., Hu, X. and Huang, Y. (2013a) Functionalized N-doped interconnected carbon nanofibers as an anode material for sodium-ion storage with excellent performance. *Carbon.* 55**.** 328-334.

Wang, Z., Xiong, X., Qie, L. and Huang, Y. (2013b) High-performance lithium storage in nitrogen-enriched carbon nanofiber webs derived from polypyrrole. *Electrochimica Acta.* 106**.** 320-326.

Watkins, D., Nuruddin, M., Hosur, M., Tcherbi-Narteh, A. and Jeelani, S. (2015) Extraction and characterization of lignin from different biomass resources. *Journal of Materials Research and Technology.* 4**.** 26-32.

Welker, M. C., Balasubramanian, K. V., Petti, C., Rai, M. K., Debolt, S. and Mendu, V. (2015) Engineering Plant Biomass Lignin Content and Composition for Biofuels and Bioproducts. *Energies.* 8.

Wu, M., Wang, Q., Li, K., Wu, Y. and Liu, H. (2012) Optimization of stabilization conditions for electrospun polyacrylonitrile nanofibers. *Polymer Degradation and Stability.* 97**.** 1511-1519.

Wu, M., Wang, Q., Liu, X. and Liu, H. (2013) Biomimetic synthesis and characterization of carbon nanofiber/hydroxyapatite composite scaffolds. *Carbon.* 51**.** 335-345.

Xiong, W., Tong, J., Yang, Z., Zeng, G., Zhou, Y., Wang, D., Song, P., Xu, R., Zhang, C. and Cheng, M. (2017) Adsorption of phosphate from aqueous solution using iron-zirconium modified activated carbon nanofiber: Performance and mechanism. *Journal of Colloid and Interface Science.* 493**.** 17-23.

Xu, D., Tan, X., Chen, C. and Wang, X. (2008) Removal of Pb(II) from aqueous solution by oxidized multiwalled carbon nanotubes. *J Hazard Mater.* 154**.** 407-16.

Yagmur, E., Inal, I. I. G., Gokce, Y., Ulusoy Ghobadi, T. G., Aktar, T. and Aktas, Z. (2018) Examination of gas and solid products during the preparation of activated carbon using phosphoric acid. *Journal of Environmental Management.* 228**.** 328-335.

Yao, S., Zhang, J., Shen, D., Xiao, R., Gu, S., Zhao, M. and Liang, J. (2016) Removal of Pb(II) from water by the activated carbon modified by nitric acid under microwave heating. *Journal of Colloid and Interface Science.* 463**.** 118-127.

Yunus, K., Ahmad, A. S., Abdullah, N. and Rashid, M. K. A. (2006) Heavy metal pollution status in the Malaysian aquatic environment AU - Shazili, Noor Azhar M. *Aquatic Ecosystem Health & Management.* 9**.** 137-145.

Yusof, N. and Ismail, A. F. (2012) Post spinning and pyrolysis processes of polyacrylonitrile (PAN)-based carbon fiber and activated carbon fiber: A review. *Journal of Analytical and Applied Pyrolysis.* 93**.** 1-13.

Zahabi, S. R., Hosseini Ravandi, S. A. and Allafchian, A. (2016) Removal of nickel and cadmium heavy metals using nanofiber membranes functionalized with (3-mercaptopropyl)trimethoxysilane (TMPTMS). *Journal of Water and Health.* 14**.** 630-639.

Zalloum, H. M., Al-Qodah, Z. and Mubarak, M. S. (2008) Copper Adsorption on Chitosan-Derived Schiff Bases. *Journal of Macromolecular Science, Part A.* 46**.** 46-57.

Zewail, T. M. and Yousef, N. S. (2015) Kinetic study of heavy metal ions removal by ion exchange in batch conical air spouted bed. *Alexandria Engineering Journal.* 54**.** 83-90.

Zhang, B., Kang, F., Tarascon, J.-M. and Kim, J.-K. (2016) Recent advances in electrospun carbon nanofibers and their application in electrochemical energy storage. *Progress in Materials Science.* 76**.** 319-380.

Zhang, L., Aboagye, A., Kelkar, A., Lai, C. and Fong, H. (2014) A review: carbon nanofibers from electrospun polyacrylonitrile and their applications. *Journal of Materials Science.* 49**.** 463-480.

Zhang, L. and Hsieh, Y.-L. (2009) Carbon nanofibers with nanoporosity and hollow channels from binary polyacrylonitrile systems. *European Polymer Journal.* 45**.** 47-56.

Zhang, X., Lin, Q., Luo, S., Ruan, K. and Peng, K. (2018) Preparation of novel oxidized mesoporous carbon with excellent adsorption performance for removal of malachite green and lead ion. *Applied Surface Science.* 442**.** 322-331.

Zhao, J., Xiuwen, W., Hu, J., Liu, Q., Shen, D. and Xiao, R. (2014) Thermal degradation of softwood lignin and hardwood lignin by TG-FTIR and Py-GC/MS. *Polymer Degradation and Stability.* 108**.** 133-138.

Zhao, R., Li, X., Sun, B., Shen, M., Tan, X., Ding, Y., Jiang, Z. and Wang, C. (2015) Preparation of phosphorylated polyacrylonitrile-based nanofiber mat and its application for heavy metal ion removal. *Chemical Engineering Journal.* 268**.** 290-299.

Zheng, J., Zhao, Q. and Ye, Z. (2014) Preparation and characterization of activated carbon fiber (ACF) from cotton woven waste. *Applied Surface Science.* 299**.** 86-91.

Zhou, J.-H., Sui, Z.-J., Zhu, J., Li, P., Chen, D., Dai, Y.-C. and Yuan, W.-K. (2007) Characterization of surface oxygen complexes on carbon nanofibers by TPD, XPS and FT-IR. *Carbon.* 45**.** 785-796.

Zhu, J., Chen, C., Lu, Y., Ge, Y., Jiang, H., Fu, K. and Zhang, X. (2015) Nitrogen-doped carbon nanofibers derived from polyacrylonitrile for use as anode material in sodium-ion batteries. *Carbon.* 94**.** 189-195.

Zulkali, M. M. D., Ahmad, A. L. and Norulakmal, N. H. (2006) Oryza sativa L. husk as heavy metal adsorbent: Optimization with lead as model solution. *Bioresource Technology.* 97**.** 21-25.