Synthesis and property of porous material for sustainable resources-based biosensor: A review

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Abstract. This paper describes the biosensor synthesis from teak lignocellulosic material. Nanocarbon was produced in drum-kiln at a temperature of 400-500°C for 7-8 hours. The activation procedure at a temperature of 800°C for 1 hour using H₂O and KOH activator and characterized by proximate analysis. Molecularly imprinted polymer (MIP) and non-imprinted polymer (NIP) techniques were applied for biosensor synthesis, while potential measurements and detection limits were used to measure product performance. This study shows that the optimal formula was a mixture of 15% MIP, 45% carbon, and 40% paraffin which produced a Nernst factor of 49.7 mV/decade and detection limit of 1.02 x 10⁻⁶ M. Related references were reviewed in this paper.

1. Introduction

Remarkable potential of lignocellulose material has been observed for the biosensor production purpose. In previous studies, bamboo and teak materials have been studied using Zn, Ni, and Cu as an intercalation material [1]. 15% KOH activator (w/w) was used in the process of activated charcoal into activated carbon [2,3] while charcoal production used simple kiln-drum technology at a temperature of 400-500°C for 6-8 hours. The characterization of both materials shows that the teak profile was superior to bamboo [1]. Properties of crystallinity degree, dielectric profile, and conductivity were the important parameters of the final product target. Activated carbon conductivity is believed to have relatively stable properties in the case of giving and receiving electrons - thus it can be used as a biosensor material. Another advantage of lignocellulose-based activated carbon is its high abundance and known as renewable materials.

One of the techniques used for biosensor production is Molecularly Imprinted Polymer (MIP) by considering the materials, apparatus, and operating units needed. Previous procedures have been carried out by Díaz-García & Fernández-González [4] including template design (target template, functional monomer); scaffold (organic polymers, inorganic polymers, polymerization techniques, cross-links), and morphological design. The nature of the scaffold greatly affects the integrity of the circuit, where biosensor accessibility is determined by the site. The macro-micro-nano pores contained in activated carbon are deciding factors in the process of moving the target ions to be captured by the template. However, it is well understood that carbonaceous materials have a wide variety of pore structures based on raw materials, production techniques, and their activation. This fact is the background of researchers to conduct research related to the pore structure of carbonaceous materials.

Enzymatic carbon electrode paste has been proven to increase electrochemical reversibility through oxidative activation on the surface of the base media and optimize biosensor response to molecular...
To be more advanced, the development of the detection of the cholinesterase enzyme which can reduce the performance of acetylcholine continues to be carried out. The nanoporous matrix produces a low linear detection range of $10^{-12}$ to $10^{-6}$ [6]. However, variations in nanoscale structure materials are still being debated, especially in the form of base materials including graphite powder, carbon nano-tubes or carbon fiber. Mobilization of electrons towards the electrodes and good biocatalytic activity are the basis of biosensor efficiency. The aim of this knowledge is to approach the sensitivity, stability, and reversibility of the electrochemical reaction in the biosensor. Vamvakaki, Tsagaraki & Chaniotakis [7] prove that carbon fiber is superior to carbon nanotubes and carbon fiber. The surface area of carbon fiber provides high sensitivity as a glucose biosensor. Indeed, a summary of the sol-gel method in the preparation of nanomaterials has been previously established, including great attention to biosensors [8]. Application of biosensors based on sustainable green materials that is increasingly being developed include: hydrogen peroxide[9], glucose determination [10–14], pathogen online detection [15], herbicide [16], melamine [17,18], ester-flavour food [19], biosensor performance and energy storage [20], hemoglobin glycation [21], acetylcholine [22], urine glucose [23] or dopamine detection [24]. This paper presents the results of previous research and a reference analysis was carried out to complement the research results.

2. The previous experiments

This paper presents previous study results on the potential of lignocellulosic stuff as a biosensor material [2]. In fact, this study is a sequence of observations on the characterization of the carbon nanostructures of lignocellulosic material [1]. References were added to this paper by including the keywords activated carbon and biosensor. At least 35 references were added to this paper and a comparison of results was put forward as a scientific consideration.

This paper discusses carbonized *Tectona grandis* using kiln-drums at 400-500°C for 7-8 hours. The carbonization product was hydrolyzed using a stainless steel reactor and the product was immersed in 15% w/w of potassium hydroxide (KOH) for 24 hours. Activation at 800°C using activator-H2O was carried out for 60 minutes. The activation product was doped with Ni with a weight ratio of 1:5, then purified at 900°C for 6 minutes. This final product was then called AC-Ni. *Molecularly Imprinted Polymer* (MIP) technique was used taking into account its simplicity and the equipment used. 0.8 mmol of monomer methacrylic acid was mixed into a 100 mL benzene solution, the crosslinker used was ethylene glycol dimethacrylate of 2.4 mmol and 0.2 mmol of melamine. A 1% benzoyl peroxide initiator was added later. The chemical mixture was refluxed at 80°C for 17 hours and the precipitate was dried in the laboratory. Filtrate washing was carried out by acetic acid, ethanol, and water at 70°C. *Non-Molecularly Imprinted Polymer* (NIP) polymer was carried out with the same procedure, without the addition of melamine.

The biosensor electrode was then formed into the micropipette tube, by mixing paraffin so that it became a carbon paste phase. 40 g of MIP/NIP was dispersed to 0.2 mL DOP and mixed into a 60 mg PVC solution in THF. The mixture was homogeneous. The micropipette tube which was filled with carbon paste was then dipped in MIP solution and dried. As a link between the electrodes with a potentiometer, a silver wire was used. Several treatments were applied to determine the electrode response (table 1).

| Electrode | MIP (%) | AC (%) | Parafin (%) |
|-----------|---------|--------|-------------|
| E-1       | 0       | 60     | 40          |
| E-2       | 0*      | 60     | 40          |
| E-3       | 5       | 55     | 40          |
| E-4       | 10      | 50     | 40          |
| E-5       | 15      | 45     | 40          |
| E-6       | 20      | 40     | 40          |

*Content of 15% NIP.*
3. The quality of activated carbon

Proximate analysis is often used to assess thermal performance in the carbonization process, activated carbon product (AC). Yield (Y,%), moisture content (MC,%), volatile matter (VM,%), ash content (AsC,%), and fixed carbon (FC,%) become parameters in studying the characteristics of carbonization products. Some studies even add Iod (I2) index parameters as reference results. Extensive thermal decomposition causes the material to release VM from the original material, although some of it remains in the solid phase. The higher temperature treatment, the less Y-AC obtained [25], even the power used affects Y, producing an effect similar to temperature [26]. Temperature alteration causes the decomposition of material to run and change composition in the material. Y-AC decreases when applied temperature treatment is above 700°C [25]. Carbon purification above 700°C provides an opportunity for carbon material to be discharged, in the form of CO, CO2, H2, CH4 or reaction products C and H2O. Increasing temperature treatment demonstrates kinetics reaction theory where an increase in temperature will trigger a faster reaction speed and cause precursor degradation. Even in chemical reagents, the degraded VM attains 96% [3]. Contrary to chemical activation, there is a chance of Y-AC addition from activator atom being attached to the AC surface, such as potassium atoms [3]. Simultaneously, both temperature and activation time affect the AC production process. What is debatable is the nominal activated precursor, the extent to which the number affects the quality of the AC. This point relates to the ability of activator (steam/chemical) to reach precursor. The nature of the original material has an indispensable influence, although it is not a significant factor compared to the treatment applied to convert the original material to AC. For example, sulfur content of origin material will determine sulfur compounds released during carbonization, which affects acid rain.

In the form of AC, the product has a high resistivity to chemical reaction [25], due to a stable double bond. Another property, in the form of AC, mineral content remains even after the carbonization and activation process. Generally, AC has a higher mineral value than the precursor. C content in AC influences the mechanical properties which are in line with mineral property. Materials with high AsC have the potential to inhibit the porous formation and reduce adsorption ability. The target of AC for waste handling applications is low AsC and MC content. AsC slightly prevents additional catalytic processes while MC anticipates the pores which are not locked [25]. However, there is a condition where MC-AC has a relative increase in chemical activation. Some water vapor molecules may be trapped in the pores and biochar hygroscopic properties when the activation process was carried out [3]. Precursor structure plays a role toward MC, like bamboo which has more cavity structures.

The indisputable fact is increasing FC-AC. Both physical and chemical activators, plus heat treatment, release functional groups of oxygen and hydrogen into volatile compounds [3]. Internal heat reaction causes only atoms to remain in solid phase while the VM and other substances are degraded in stages. Another parameter is I2 index, which shows the ability of adsorption that increases dramatically compared to the original material. I2 is a synthetic dye that is very concentrated and difficult to absorb. Thus, the ability of porous carbon is to be tested against I2, furthermore, an increase in the I2 index is a hallmark of good adsorption ability. The intensity of macro and micro

| Table 2. List of activated carbon precursors and their quality. |
|---------------------------------------------------------------|
| Researcher | Yield (%) | MC (%) | VM (%) | AsC (%) | FC (%) | Iod (mg·g⁻¹) | Material |
|------------|-----------|--------|--------|---------|--------|-------------|----------|
| This paper | 28.9-46.6 | 1.1-13.7 | 5.6-16.02 | 2.62-8.9 | 81.4-85.4 | 264.4-865.2 | T. grandis, Palm kernel shell |
| Lam, Su, et al. [26] | 81-87 | 2.4-2.7 | 5.0-5.9 | 3.0-3.6 | 88.1-89.3 | - | Tobacco |
| Gonsalvesh et al. [27] | 29.3-38.6 | 3.0-4.3 | 4.1-15.6 | 28.0-51.1 | 43.8-67.5 | - | Date stone shell |
| [28] | 21.6 | 7.17 | 5.13 | 5.85 | 89.02 | 814 | Waste palm shell |
| [29] | 12-17 | 3.0-4.4 | 16.0-21.1 | 4.0-6.0 | 77-2.8 | - | Waste palm shell |
| [25] | 68.4-97.8 | 2 | 22 | 4 | 73 | 9-47.0 | Teak, bamboo sawdust |
| [3] | 24.9-80.1 | 2.55-7.72 | 2.01-14.71 | 4.79-16.45 | 74.47-90.64 | 222.3-833.6 | |
| [30] | 46.51-97.36 | 2.53-5.71 | 4.39-18.04 | 36.55-50.56 | 37.99-52.25 | 363.5-668.6 | |
pore formation by heat is responsible for improving the adsorption properties of the product. A clear sign that internal pore formation occurs is when cellulose, hemicellulose, and lignin are overhauled to become volatile and mild gases by treatment. Finally, it can be notified that the quality of AC is influenced by precursor, carbonization, and activation treatment and target of AC production (table 2).

4. The structure and surface morphology of activated carbon

The surface area of AC of this paper was 280.26 m². g⁻¹, 917.11 m². g⁻¹ and 692.22 m². g⁻¹, while the degree of crystallinity was 25.98%, 36.10%, and 38.88%, respectively for charcoal, AC-steam, and AC-KOH [2]. Surface morphology is part of AC that reacts with reactants, thus good morphology indicates the optimum performance of electrons surrounding the AC surface while the degree of crystalline provides notification of arrangement of carbon at regular distances and leaves amorphous behavior. This surface structure and morphology formation involve dehydration and elimination reactions during the carbonization and activation process. Again, the profile of the original material and treatment have different effects on the structure and morphology of targeted AC.

During the activation process, whether physical or chemical, the activation time is important in the preparation of macro-meso-micropores (figure 1). In AC form, pores are more uniform with smaller pores found on the inside and or around larger pores. Under certain conditions, steam activation results in a superior product compared to steam activation that contains N₂ [31]. An increase in activation time pushes the AC to be more porous than before. But at a certain time limit, it triggers cracks in the internal pore which causes pore deformation and decreases porous properties [26]. This phenomenon is difficult to predict, but knowledge of precursor profiles becomes mandatory. Porous structure causes AC to provide more sites for adsorption performance. Adsorption efficiency of AC is determined by porosity, surface character, pore size [26], and pore distribution. The interconnection of the aromatic ring layer is restored during the activation process to form a macro-micro-nano pore. Therefore, the structure and morphology of AC are more onward compared to the original material. Carbonization and activation methods will determine the course of the structure of carbon material to be more advanced. Among them is the microwave technique that is superior to the carbon stockpile technique or activation in a modified reactor. The thermal efficiency of microwaves can minimize cracks that release carbonized product content [29]. The hierarchical structure of carbon material follows a sequence of precursors, carbonized products (biochar), and activated carbon. The last product has a high profile compared to the previous structure. For AC application, pore size is the target achieved in the synthesis procedure. The gas molecular distance was 0.4-0.9 nm while the molecular size of liquid was > 27 nm [32]. Thus 3 types of pore distribution from AC: macropore (>50 nm), mesopore (2-50 nm), and micropore (<2 nm) become unique properties for various applications. Precursors that have dominant cellulose content produce high micropore distribution, while lignin material forms macro pores [31]. Mesopores are known to be formed through a volatile overhaul of the process of carbonization and pyrolysis in stages. Exposure to steam forms micro and mesopores in carbon fiber which was a product of the interaction between water molecules and carbon atoms [33]. Isotherm deformation at relatively low pressures was the formation of micro-pores typical for adsorbents [31]. A phenomenon of structure and morphology differences in the same treatment was affected by the chemical composition of the precursor. Even in one individual plant, there are a variety of different organic chemical contents, for example, roots, stems, branches, twigs, or leaves.

The reaction by N₂ ran slower than the reaction by water vapor. N₂ blast was superior in structural but less porous than H₂O activation [31]. This statement is marked by yield (%) of AC-steam products against AC-N₂ product, the solid phase was overhauled to become volatile which was heated up by heat. This condition continues to change with increasing temperature and activation time. But this approach needs to get further clarification which is more comprehensive. On the other hand, organic chemical composition affected resistance in the process of activation by N₂. The tar content of the original material had a stable reaction compared to material that had dominant furfural [31]. The ultimate analysis shows the reactions that occurred in the furnace. An increasing portion of O₂ in AC indicates carbon was oxidized during the activation process, and this was important in pores formation of AC. Referring to the above statements, precursors with high furfural might have more oxygen functional groups. There were different conditions when using KOH as an activation agent. Element K
diffused into the deepest carbon layer and reconstructed the internal pores [34], whether by forming new pores or cracking pores that had been formed before. Thus, AC product by KOH activation was superior to steam and steam-N₂.

![Surface morphology of different activated carbons (AC).](image)

**Figure 1.** Surface morphology of different activated carbons (AC).
(a) Pari, Santoso, Hendra, et al. [2]
(b) (c) (d) Lee et al. [25]
(b) Waste palm shell (WPS)
(c) Carbonized WPS
(d) AC-WPS
(e) (f) (g) Lam et al. [35]
(h) Nieto-Delgado, et al [36]

In all heat treatment techniques, every single step of activation changed significantly in morphology compared to the precursor. Thermal deformation caused the inner structure to shrink and rearranged the chemical bond. Macropore structural deformation was formed due to differences in thermal decomposition in a biopolymer that formed a cell wall [36] and the S2 layer played a key role
related to its most dominant layer in the cell wall. The target application determined if the activation technique used was drawn backwards. Simply, physical activation was superior to chemical activation, information of functional groups, although it was not a rule. Oxidation of carbon surfaces during steam activation was responsible for this point.

The degree of crystallinity demonstrates the order of the aromatic layer. Carbon reconstruction was characterized by increasing crystalline properties and leaving irregular (amorphous) properties. The transformation of the degree of crystallinity is shown in Figure 2. Changes in the structure of precursors, carbonization products, AC, and AC-Ni show improved character. The intense peak changes on theta-43 become a characteristic of carbonous material. Ni metal atoms were successfully intercalated into carbon atoms, crystal structures of 100 and 102 [2]. Thermal treatment played an important role in a better and more conductive arrangement of aromatic layers (symmetrical and crystalline).

![Figure 2](image)

**Figure 2.** *Tectona grandis* diffractogram: (a) precursor (b) carbonized (c) AC-HOH&KOH (d) AC-Ni [2].

5. The electrical properties of activated carbon electrodes

The third generation is deemed necessary to get supporting material for the development of integrated circuits in the future. Nano-sized activated carbon is a solution that is offered with the availability of resources for production and low-cost matter. The superiority of this porous material allows electron transfer between electrodes to run effectively between redox reactions.

Resistance and dielectric behavior represent AC electrical properties, while supercapacitor electrode performance by potential measurement and detection limits calculation. KOH activator in this paper had significantly reduced the value of AC resistance, it was noted of 0.0 – 0.78 Ω [2]. Potassium from KOH, which was an alkali metal, had been shown to increase the conductivity behavior of AC. Intercalation of Ni and activator-KOH increased the ability to conduct electricity of
AC, even silver which had the most conductive conductor properties. The surface area, total volume, and relatively small temperature changes become inherent properties of the AC to improve the conductor level. Electron transfer was performed at range 18.0 – 2,733.3 S/m [2]. This paper demonstrated good carbon paste and MIP at slope 54 with 49.7 mV/decade Nernst factor and detection limit of $1.02 \times 10^{-6}$ M [2] for melamine solution $10^{-8} – 10^{-2}$ M at pH 4.

Rovina et al. (2015) conducted a study with a wider detection limit of $9.6 \times 10^{-16}$ while developing melamine detection in the food industry. Green resource-based melamine biosensor was used as an instrument due to its simplicity, rapidity, stability, selectivity, sensitivity, wide detection distance, and affordable method. The AC-based biosensor was reported to increase stability and reduce detection limits 1000-fold, $10^{-12} – 10^{-6}$ [6].

6. Conclusion

Sustainable resources Tectona grandis have tremendous potential as biosensor material. The structural conversion of Tectona grandis to activated carbon is a mandate for the application of biosensor. A variety of activated carbon production techniques is an opportunity, where the stable nature of the chemical reaction, the porous structural hierarchy, and decreased detection limits are inherent products. This paper has presented KOH as an activator and Ni metal as a doping agent with a ratio of 1: 5 in activated carbon production, as a follow-up of previous research. Molecularly Imprinted Polymer (MIP) technique was used due to the ease and simplicity of the equipment. The ideal composition was achieved with carbon, MIP, and paraffin portions of 45%: 15%: 40%, respectively, for melamine solution of $10^{-8} – 10^{-2}$ M at pH 4.

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References

[1] Pari G, Santoso A, Hendra D, Bukhari B, Maddu A, Rachmat M, Harsini M, Heryanto T and Darmawan S 2013 Characterization of Carbon Nano Structure from Lignoscellulose Material J. Forest Products Research 31 75–91
[2] Pari G, Santoso A, Hendra D, Bukhari, Maddu A, Rachmat M, Harsini M, Safitri B A, Heryanto T and Darmawan S 2016 Possible Application of Ligno-cellulose Nano Carbon as Biosensor J. Forest Products Research 34 111–26
[3] Pari G, Santoso A, Buchari D H and Maddu A 2016 The Potency of Nano Carbon Structure Made from Bamboo and Teak Wood Lignocellulose J. Forest Products Research 34 309–22
[4] Díaz-García M E and Fernández-González A 2004 Molecularly Imprinted Polymers Encyclopedia of Analytical Science: Second Edition pp 172–82
[5] Motta N and Guadalupe A R 1994 Activated Carbon Paste Electrodes for Biosensors Anal. Chem. 66 566–71
[6] Sotiropoulou S and Chaniotakis N A 2005 Lowering the detection limit of the acetylcholinesterase biosensor using a nanoporous carbon matrix Anal. Chim. Acta 530 199–204
[7] Vamvakaki V, Tsagarakis K and Chaniotakis N 2006 Carbon Nanofiber-Based Glucose Biosensor Anal. Chem. 78 5538–42
[8] Díaz-García M E and Laiño R B 2005 Molecular imprinting in sol-gel materials: Recent developments and applications Microchim. Acta 149 19–36
[9] Song J, Xu J M, Zhao P S, Lu L De and Bao J C 2011 A hydrogen peroxide biosensor based on direct electron transfer from hemoglobin to an electrode modified with Nafion and activated nanocarbon Microchim. Acta 172 117–23
[10] Şavk A, Aydin H, Cellat K and Şen F 2020 A novel high performance non-enzymatic electrochemical glucose biosensor based on activated carbon-supported Pt-Ni nanocomposite J. Mol. Liq. 300 112355
[11] Koskun Y, Şavk A, Şen B and Şen F 2018 Highly sensitive glucose sensor based on monodisperse palladium nickel/activated carbon nanocomposites Anal. Chim. Acta 1010 37–
[12] Khalifa A M, Abdulateef S A, Kabaa E A, Ahmed N M and Sabah F A 2020 Study of acidosis, neutral and alkalosis media effects on the behaviour of activated carbon threads decorated by zinc oxide using extended gate FET for glucose sensor application Mater. Sci. Semicond. Process. 108 104911

[13] Im J S, Kim J G, Bae T S, Yu H R and Lee Y S 2011 Surface modification of electrospun spherical activated carbon for a high-performance biosensor electrode Sensors Actuators, B Chem. 158 151–8

[14] Kim J H, Lee D, Bae T S and Lee Y S 2015 The electrochemical enzymatic glucose biosensor based on mesoporous carbon fibers activated by potassium carbonate J. Ind. Eng. Chem. 25 192–8

[15] Upadhyayula V K K, Deng S, Smith G B and Mitchell M C 2009 Adsorption of Bacillus subtilis on single-walled carbon nanotube aggregates, activated carbon and NanoCeram™ Water Res. 43 148–56

[16] Tucci M, Grattieri M, Schievano A, Cristiani P and Minteer S D 2019 Microbial amperometric biosensor for online homicide detection: Photocurrent inhibition of Anabaena variabilis Electrochim. Acta 302 102–8

[17] Rovina K, Siddiquee S and Wong N K 2015 Development of melamine sensor based on ionic liquid/nanoparticles/chitosan modified gold electrode for determination of melamine in milk product Sensors Actuators, B Chem. 158 151–8

[18] Alam M M, Asiri A M, Uddin M T, Inamuddin, Islam M A, Awual M R and Rahman M M 2019 One-step wet-chemical synthesis of ternary ZnO/CuO/Co3O4 nanoparticles for sensitive and selective melamine sensor development New J. Chem. 43 4849–58

[19] Madhu R, Veeramani V, Chen S M, Veerakumar P, Liu S Bin and Miyamoto N 2016 Functional porous carbon-ZnO nanocomposites for high-performance biosensors and energy storage applications Phys. Chem. Chem. Phys. 18 16466–75

[20] Wang L, Chen X, Liu C and Yang W 2016 Non-enzymatic acetylcholine electrochemical biosensor based on flower-like NiAl layered double hydroxides decorated with carbon dots Sensors Actuators, B Chem. 233 199–205

[21] Lee C L, Yek P N Y, Lam S S, Chuah J H, Liew R K, Park Y-K and Osman M S 2019 Microwave steam activation, an innovative pyrolysis approach to convert waste palm shell into highly microporous activated carbon J. Environ. Manage. 236 245–53

[22] Lam S S, Su M H, Nam W L, Thoo D S, Ng C M, Liew R K, Yuh Yek P N, Ma N L and Nguyen Vo D V 2019 Microwave Pyrolysis with Steam Activation in Producing Activated Carbon for Removal of Herbicides in Agricultural Surface Water Ind. Eng. Chem. Res. 58 695–703

[23] Gonsalvesh L, Yperman J, Carleer R, Mench M, Herzig R and Vangronsveld J 2016 Valorisation of heavy metals enriched tobacco biomass through slow pyrolysis and steam activation J. Chem. Technol. Biotechnol. 91 1585–95

[24] Akila E, Pugalendhi S, Subramanian S, Duraisamy P, Duraisamy M R and Surendrakumar A 2019
Production and characterization of activated carbon from date stones by single step steam activation. *Environ. Ecol.* **37** 194–7

[29] Lam S S, Yuh Yek P N, Ok Y S, Chong C C, Keey Liew R, Tsang D C W, Park Y-K, Liu Z, Wong C S and Peng W 2019 Engineering pyrolysis biochar via single-step microwave steam activation for hazardous landfill leachate treatment *J. Hazard. Mater.* **390** 121649

[30] Pari G, Tohir D, Mahpudin and Ferry J 2006 Activated Charcoal from Wood Sawdust as Adsorbent Material for Frying Oil Refinery *J. Forest Products Research* **24** 309–22

[31] Savova D, Apak E, Ekinci E, Yardim F, Petrov N, Budinova T, Razvigorova M and Minkova V 2001 Biomass conversion to carbon adsorbents and gas *Biomass and Bioenergy* **21** 133–42

[32] Danish M and Ahmad T 2018 A review on utilization of wood biomass as a sustainable precursor for activated carbon production and application *Renew. Sustain. Energy Rev.* **87** 1–21

[33] Manickam S S, Waisi B I, Nijmeijer A, McCutcheon J R and Benes N E 2019 Activated Carbon Nanofiber Nonwovens: Improving Strength and Surface Area by Tuning Fabrication Procedure *Ind. Eng. Chem. Res.*

[34] Rostamian R, Heidarpour M, Mousavi S F and Afyuni M 2015 Characterization and sodium sorption capacity of biochar and activated carbon prepared from rice husk *J. Agric. Sci. Technol.* **17** 1057–69

[35] Lam S S, Liew R K, Wong Y M, Yek P N Y, Ma N L, Lee C L and Chase H A 2017 Microwave-assisted pyrolysis with chemical activation, an innovative method to convert orange peel into activated carbon with improved properties as dye adsorbent *J. Clean. Prod.* **162** 1376–87

[36] Nieto-Delgado C, Partida-Gutierrez D and Rangel-Mendez J R 2019 Preparation of activated carbon cloths from renewable natural fabrics and their performance during the adsorption of model organic and inorganic pollutants in water *J. Clean. Prod.* **213** 650–8