Nanoparticle-templated conversion of glucose to a high surface area biocarbon for the removal of organic pollutants in water

Luis A. Barrera, Alma C. Escobosa, Aileen Nevarez, Md. Ariful Ahsan, Laila S. Alsaihati and Juan C. Noveron

ABSTRACT

While extensive work has been done on the generation of adsorbents by carbonization of large polymeric structures, few works are currently available for the use of monomeric carbon molecules as precursors during carbonization. In this work we report the formation of a carbon adsorbent material from the carbonization of glucose in the presence of zinc oxide (ZnO) nanoparticle templates. Carbonization at 1,000 °C under inert atmosphere yields a product with Brunauer–Emmett–Teller (BET) surface area of 1,228.19 m²/g and 14.77 nm average pore diameter. Adsorption capacities against methylene blue, 2-naphthol and bisphenol-A at pH 7 were found to be 539 mg/g, 737 mg/g and 563 mg/g, respectively. Our material demonstrates a strong fit with the Langmuir isotherm, and adsorption kinetics show regression values near unity for the pseudo-second order kinetic model. A flow adsorption column was implemented for the remediation of tap water containing 20 mg/L methylene blue and found to quantitatively purify 11.5 L of contaminated water.

Key words | adsorbent, carbonization, mesoporous, monomer, remediation

HIGHLIGHTS

- Synthesis of high adsorption capacity adsorbent using glucose was achieved.
- Achieved a high surface area of 1228 m²/g and small average porosities of 14.74 nm.
- Graphenic structure observed by XRD analysis.
- High adsorption capacity for methylene blue (539 mg/g), 2-naphthol (737 mg/g) and bisphenol-A (563 mg/g) at neutral pH.
- Fast adsorption kinetics for methylene blue, 2-naphthol and bisphenol-A were observed.

INTRODUCTION

The presence of organic contaminants in water is of pressing concern due to the harmful effects which can occur from prolonged exposure to these chemicals. Amongst these contaminants are dyes and dye precursors, such as methylene blue (MB) and 2-naphthol, respectively. As many as 7 × 10⁵ tons of dye are produced annually, and although the US Environmental Protection Agency (EPA) has recommended limits at 0.2 mg/L, up to 15% of the dyes are lost in the effluent during the dyeing process (Pardo et al. 2018). Ingestion of MB can result in nausea, vomiting, mental confusion and even methemoglobinemia (Ghosh & Bhattacharyya 2002). Organic dyes have also been shown to be detrimental to aquatic life (Rizzo et al. 2013). Since many dyes are resistant to light, oxidizing agents, and

biodegradation, one of the best approaches for the removal of these contaminants from water is adsorption (Mohan et al. 2014).

Phenolic compounds such as 2-naphthol are another group of organic water contaminants which can be highly detrimental to our health, as can be evidenced by their inclusion on the priority pollutant list by the US Environmental Protection Agency, with a maximum concentration in individual phenolic compounds not to exceed 0.1 μg/L (Mahugo Santana et al. 2009). 2-Naphthol is used in many industrial products, predominantly pesticides, oil and their residues, and Sudan dyes (Krugly et al. 2015). Studies have shown that ingestion of water contaminated with 2-naphthol can result in kidney malfunction and problems with blood circulation in humans (He et al. 2010). To complicate matters, these pollutants have also shown high resistance to light, heat, biodegradation and moderate oxidizing conditions, making their remediation complicated (Cheng et al. 2015).

Bisphenol-A (BPA), a plasticizer used for the widespread synthesis of polycarbonate plastics and epoxy resins, is another common organic contaminant in water. BPA falls in a class of organic molecules called synthetic estrogens, many of which are believed to contribute to breast, prostate and testicular cancers (Maffini et al. 2006). Three million tons of BPA were estimated to have been produced worldwide in 2003 (Mileva et al. 2014), and despite bans to prevent BPA from being used in items such as children’s food and drink containers, BPA production remains high (Seachrist et al. 2016). BPA has been shown to induce mutations in ovarian cells and increase cell proliferation in breast and prostate cells (Nomiri et al. 2019).

Remediation of water from organic pollutants such as the ones mentioned here has received much attention, with methods such as physical adsorption (Khan et al. 2018), chemical reduction/oxidation (Islam et al. 2016, 2017b), electrochemical degradation (Padilla et al. 2018), photocatalytic degradation (Islam et al. 2018), and even biological methods (Homem & Santos 2011) having been implemented for the removal and/or degradation of these contaminants. From these methods, adsorption is often the preferred method for remediation due to its low cost and ease of use, with activated carbons seeing the most success in real world applications. Common methods of generating activated carbons include physical (Ahmadpour & Do 1996) and/or chemical processes (Caturia et al. 1991), most of which employ large polymeric carbon sources (such as lignocellulosic materials) and metal salts or acids such as zinc chloride or phosphoric acid for activation (Rodríguez-Reinoso & Molina-Sabio 1992). Activation of these polymeric carbons for the production of biochar requires soaking the material in water containing these acids for long periods of time, which may result in a less than ideal homogeneity along its fibrous network. This lack of homogeneity can result in a porous adsorbent with drastically different surface area and pore size from one region to another, or even from batch to batch. To achieve a highly homogeneous carbon mixture before carbonization, we employ zinc oxide nanoparticles as a sacrificial template around which glucose can intercalate. Few studies have been done on the carbonization of monomers such as glucose as the carbon source and nanoparticles such as zinc oxide as templating agents for the generation of porosities (Guo et al. 2007; Ding et al. 2008; Wang et al. 2018; Barrera et al. 2019).

Herein we propose the carbonization of glucose in the presence of zinc oxide nanoparticles to form an adsorbent material for the remediation of water from MB, 2-naphthol and BPA. A homogeneous mixture of the two was carbonized under inert atmosphere at 1,000 °C for 2 h, resulting in the reduction of Zn(II) and sublimation of zinc(0) (Wang et al. 2015), yielding a porous carbon material in-situ which we refer to as nanotemplated carbon (NTC). This material was then characterized by X-ray diffraction (XRD), Brunauer–Emmett–Teller (BET), Barrett–Joyner–Halenda (BJH) and elemental mapping. Its adsorption properties were analyzed under various concentrations and pH, and the data was modeled using the Langmuir and Freundlich isotherm models. Its kinetic properties were also explored, with the data further analyzed using pseudo-first order, pseudo-second order and intraparticle diffusion kinetic models.

MATERIALS AND METHODS

Preparation and carbonization of glucose-nanoparticle mixtures

For the preparation of glucose-zinc oxide (Glc-ZnO) mixture (1:1 wt:wt), 1.5 g of glucose and 1.5 g of ZnO NPs were dissolved/suspended in 20 mL of reverse osmosis (RO) water. The mixture was sonicated for 30 min and subsequently stirred for another 30 min. At this point the water was evaporated under reduced pressure using a rotary evaporator until mostly dry. The Glc-ZnO mixture was further allowed to dry under reduced pressure via vacuum pump overnight.
When fully dry, the Glc-ZnO mixture was weighed, transferred to a quartz crucible and placed in the furnace. In order to maintain an inert atmosphere, the furnace was argon-flushed for 30 min prior to carbonization, then carbonized under constant argon flow for 2 h at 1,000 °C with a ramp speed of 10 °C/min, with a yield of 0.239 g carbonized material.

Adsorption capacity and kinetic studies

All adsorption capacity studies were performed in triplicate using 10 mg of NTC or activated carbon (AC) and 10 mL of the target contaminant solution. Adsorption capacity solutions were done at three separate pH (pH 3, pH 7 and pH 10) and at four separate concentrations (250, 500, 750 and 1,000 mg/L). Adsorption capacity studies were done at room temperature under stirring over 24 h, at which point they were centrifuged and the supernatant diluted for analysis by UV-Vis spectroscopy. All dilutions were made using water adjusted to the corresponding pH for the study. Wavelengths used for UV-Vis analysis were 664 nm for MB, 275 nm for BPA and 274 nm for 2-naphthol.

Kinetic studies were performed in triplicate using 15 mg of NTC or AC and 15 mL of the target contaminant. All contaminant solutions were done at a concentration of 100 mg/L at a pH of 7 (±/-0.2). One mL aliquots were taken at 0 s, 15 s, 30 s, 1 min, 2 min, 5 min, 15 min, 30 min, 1 h, 2 h and 4 h, and subsequently filtered through a 0.2 μm PTFE syringe filter. Aliquots for UV-Vis spectroscopy analysis for MB were diluted to 10%. 2-naphthol and BPA aliquots were measured directly after filtration.

Experimental data modeling

Langmuir and Freundlich adsorption isotherm models were applied to the pH dependent adsorption capacity data, while pseudo-first order, pseudo-second order and intra-particle diffusion models were applied to the kinetic experiments data. A summary of each model can be found in the supplemental material.

Characterization

Carbonization was performed using a GSL-1100X from MTI Corporation. The crystal structure analysis of the carbon material and the embedded nanoparticles was performed on a Panalytical Empyrean 2 diffractometer (Cu anode, Kα radiation, λ = 1.54 nm) with a scan rate of 1.7 deg/min. A Hitachi S-4800 instrument was used for scanning electron microscopy (SEM) as well as EDS imaging. Samples for energy dispersive X-ray spectroscopy (EDS) were placed as powders in 12 mm diameter carbon adhesive tabs. UV-Vis adsorption measurements were taken through a 10.00 mm quartz cuvette using a NU-T6PC instrument purchased from Zhengzhou Nanbei Instrument Equipment corporation. The specific surface area and BJH adsorption measurements were taken using a Micrometrics surface area analyzer TriStar II 3020 instrument. Samples were heated at 85 °C and degassed overnight prior to analysis. Nitrogen adsorption–desorption isotherms were measured at 78 K in flowing nitrogen.

RESULTS AND DISCUSSION

X-ray diffraction

X-ray diffractograms for NTC as well as control ZnO nanoparticles can be seen in Supplemental Figure 1. After carbonization at 1,000 °C for 2 h under argon, we observe none of the characteristic ZnO diffractogram peaks left in our material. This is expected, as Zn(II) can be reduced by carbon at temperatures exceeding 900 °C, at which point they become volatile and sublime from the reaction mixture (Wang et al. 2015). For the 2θ range of 20–80 degrees we observe no sharp signals in our material, indicating a highly amorphous composition. However, the appearance of a small, broad signal at 29.5 degrees is attributed to the carbon material itself, as graphenic carbons have been observed to show this broad (0 0 2) reflection in the 2θ range between 20 and 50 degrees (Bindumadhavan et al. 2013; Chen et al. 2015). In addition, the broad peak centered around 43° indicates the presence of honeycomb structures formed by sp² hybridized carbons (Fey et al. 2005).

Energy dispersive X-ray spectroscopy

Elemental mapping of NTC shows the bulk of the material is composed of carbon and oxygen, as expected (Figure 1). Supplemental Table 1 summarizes the atomic percentages present in the material. We observe a carbon atomic composition of 90.2%, with oxygen making up another 8.2%. The other 1.6% atomic composition is due to impurities such as sodium, magnesium, aluminum, silicon, phosphorus, as well as some tin and molybdenum. These impurities can be attributed to contaminated crucible, quartz tube, desiccator, and general laboratory ambient. The high carbon content is expected, as glucose undergoes large amounts of
dehydration at these high temperatures under inert atmosphere. The majority of the lost mass is attributed to the loss of ZnO, as well as water and small COx species (Carlson et al. 2009).

BET and BJH analysis

Pyrolysis parameters have a large impact upon the physical characteristics of the carbonized material (Han et al. 2014). Surface area in particular is largely affected by pyrolysis temperature. In general, increased pyrolysis temperature results in a higher surface area material, up to a certain threshold. This trend was observed in our material, as pyrolysis at a temperature of 1,000 °C resulted in a substantial surface area of 1,228.19 m²/g (Supplemental Figure 2A). The adsorption/desorption curve for NTC fits a Type IV isotherm model, indicating a porous material with low energy for adsorbent-adsorbate interaction. From the BJH adsorption isotherm (Supplemental Figure 2B) we can see that a large portion of the pore volume is allocated to cavities with pore width between 10 and 100 nm, with a calculated BJH adsorption average pore width of 14.74 nm. However, a large amount of area is shown for cavities under 5 nm in width, as can be seen in Supplemental Figure 2C. Our material has pores in the range of micro- (<2 nm), meso- (2–50 nm) and macroporosities (>50 nm).

Transmission electron microscopy

Transmission electron microscopy images of NTC (Supplemental Figure 3) shows a highly irregular, porous material. The average diameter of these porosities was calculated to be 20.79 nm by ImageJ software. Smaller porosities were observed, and these porosities were calculated to have an average diameter of 3.14 nm by ImageJ software. Averaging both the larger and smaller porosities together, we calculate an overall average pore diameter size of 16.37 nm, which is in agreement with the 14.74 nm pore width calculated from BJH.

Adsorption capacity and pH-dependent studies

Adsorption capacity and pH dependent studies for NTC against MB, 2-naphthol and BPA were performed. Molecular structures of the contaminants can be seen in Supplemental Figure 4, and the adsorption curves can be seen in Figure 2. For methylene blue (Figure 2(a)) we can see the general trend of higher adsorption capacity as pH increases. At acidic pH, adsorption capacity seems to reach a limit at 313 mg/g. As the pH is increased to neutral, adsorption capacity also increases to 539 mg/g, while adsorption capacity at basic pH it reaches 877 mg/g, nearly a 1:1 adsorbent/adsorbate ratio. This trend can be attributed to the overall charge of methylene blue at these different pH levels. Under acidic conditions, the amine in methylene blue can become protonated, resulting in a net-positive charge in the molecule. This interferes with its adsorption onto our material, which consists mostly of C-C sigma and pi bonds and thus adsorbs mostly molecules which are net-neutral in nature via hydrophobic and π-π interactions. These positive charges in methylene blue result in repulsion between adjacent molecules adsorbed onto our material, decreasing the overall adsorption capacity. At neutral pH methylene blue is deprotonated once again, resulting in a net-neutral molecule which can more easily interact with our hydrophobic adsorbent without repulsion from adjacent molecules. In fact, this trend is prevalent even at pH 10 up to 750 mg/L concentration, where the adsorption of methylene blue onto our material is nearly equivalent at both pH 7 and pH 10. At a concentration of 1,000 mg/L and pH 10 we can see another increase in adsorption onto our material, possibly due to a shift towards a Freundlich adsorption model where adsorption is multilayered, not single-layered as in a Langmuir model.
Adsorption of 2-naphthol onto NTC (Figure 2(b)) is also highly pH-dependent. At acidic pH we observe the lowest adsorption onto our material, reaching an experimental maximum of 303 mg/g. Under these conditions, the hydroxyl in 2-naphthol can become protonated, resulting in a net-positive charge which not only interferes with adsorption onto a hydrophobic layer, but also results in repulsion between neighboring adsorbates on the surface, resulting in sub-optimal adsorption. Under basic conditions, we see a rise in the adsorption maximum to 421 mg/g due to deprotonation of the hydroxyl, resulting in a net negative charge. However, this charge is resonance stabilized and distributed throughout the molecule. This distribution of charge is perhaps responsible for the higher adsorption of 2-naphthol onto our material at pH 10 over pH 3, where the positive charge is localized at a single point. At neutral pH we observe the highest experimental adsorption capacity at 737 mg/g due to the hydroxyl remaining protonated, resulting in a net-neutral molecule which can better interact with our hydrophobic material without repulsion from nearby molecules.

Adsorption of BPA (Figure 2(c)) follows a similar trend to the adsorption of 2-naphthol onto our material. At basic pH, BPA becomes deprotonated, thus affecting its adsorption onto the hydrophobic adsorbent and resulting in an adsorption maximum of 392 mg/g. At pH 3 there is the possibility of protonation of one of the hydroxyls, which results in a slightly higher adsorption maximum of 459 mg/g. As with 2-naphthol, we see the highest experimental adsorption capacity (563 mg/g) under neutral conditions, attributed to the absence of a net charge on BPA and higher interaction with the adsorbent.

Adsorption capacities for a commercially available AC were also studied under these conditions and can be seen in Figure 2(d)–2(f). Adsorption of MB by AC follows a similar trend as with NTC, with the lowest adsorption happening at acidic pH (332 mg/g). Under neutral conditions, adsorption is slightly increased (365 mg/g), while at basic pH we observe the highest adsorption capacity of MB onto AC (705 mg/g). Adsorption of 2-naphthol also has the lowest Qe under acidic conditions (257 mg/g), with a higher adsorption capacity at neutral pH (382 mg/g) and the highest Qe present under basic conditions (512 mg/g). The highest adsorption capacity for BPA happens under neutral pH (974 mg/g), much like with NTC. Basic conditions show a slight decrease in the adsorption capacity of BPA (831 mg/g) while acidic conditions have a drastic effect in the adsorption capacity (499 mg/g).
It should be noted that under acidic conditions, adsorption of all three contaminants by both NTC and AC is the lowest, indicating that electrostatic repulsion between the adsorbates is too large to be overcome by adsorbate/adsorbent interactions. At pH 10, however, BPA adsorption by AC is quite higher than by NTC, indicating the presence of possible groups in AC which can interact electrostatically with the negatively charged BPA molecules; this group appears to be absent in NTC. Adsorption of MB and 2-naphthol by both NTC and AC is relatively similar, indicating a larger pH effect on BPA than either of the other two contaminants, which in turn increased its adsorption onto AC. Of greater interest to us are the adsorption capacities under neutral conditions, for which NTC had significantly higher adsorption towards MB and 2-naphthol than AC. This indicates that our material has a large adsorption potential towards neutral and aromatic organic molecules due to its large surface area and sp²-hybridized carbon composition.

Adsorption isotherms

The Langmuir and Freundlich isotherms for NTC adsorption capacity experiments can be seen in Supplemental Figure 5, with Supplemental Table 2 summarizing the adjusted R² value for each. We can see good correlation by the Langmuir isotherm for MB and BPA at all pH levels, with R² values ranging from 0.91384 to 0.99998. Freundlich values for MB were much lower (0.65518 at pH 3, 0.49276 at pH 7 and 0.33843 at pH 10), indicating that the adsorption of MB by our adsorbent more closely resembles a single layer, Langmuir-type adsorption pattern at all three pH ranges. Interestingly, adsorption of 2-naphthol onto our adsorbent more closely resembles a Freundlich adsorption pattern (R² = 0.96328) than a Langmuir pattern (R² = 0.62587) at pH 3, while at pH 7 and pH 10 the R² values for Langmuir (0.99895 and 0.9983, respectively) are closer to 1 than those for Freundlich (0.89125 and 0.9991, respectively). Adsorption of BPA shows higher coefficient of determination for the Langmuir isotherm over the Freundlich isotherm at pH 3 and pH 7. At a pH of 10, both the Langmuir and Freundlich isotherms show a good fit for the adsorption of BPA, with the Freundlich isotherm fit being slightly higher than Langmuir.

Experimental and calculated adsorption maxima (Qmax) values can be seen in Table 1. With the exception of MB at pH 10, we observe good correlation between experimental and calculated Qmax values. The intensity of adsorption (1/n) values for all adsorbates were calculated from the slope of each Freundlich isotherm. Intensity of adsorption values of 1/n under 0 (negative) are considered irreversible adsorptions. Values of 1/n between 0 and 1 are considered desirable, and values of 1/n greater than 1 are considered undesirable. From Table 1 we can see that all intensity of adsorption values fall between 0 and 1, indicating desirable adsorption conditions of the adsorbates onto NTC at all three pH. The Langmuir (K_L) and Freundlich (K_F) constants, as well as the dimensionless equilibrium parameter R_L, were calculated and their values summarized in Table 1. Calculations for K_L and R_L can be found in Equations (1) and (2), respectively.

\[
K_L = \frac{1}{Q_{\text{max}} y_{\text{intercept}}} \tag{1}
\]

\[
R_L = \frac{1}{1 + K_L C_i} \tag{2}
\]

where Q_max is the maximum calculated adsorption, y_intercept is the y-intercept of the C_e/Q_e vs C_e Langmuir plot for the given adsorbent and pH, K_L is the Langmuir constant, and C_i is

<table>
<thead>
<tr>
<th>pH</th>
<th>Qmax (mg/g)</th>
<th>1/n</th>
<th>K_L</th>
<th>R_L</th>
<th>K_F</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>313.1</td>
<td>0.05194</td>
<td>0.05298</td>
<td>0.01852</td>
<td>5.478</td>
</tr>
<tr>
<td>7</td>
<td>539.9</td>
<td>0.1023</td>
<td>0.8894</td>
<td>0.001123</td>
<td>5.739</td>
</tr>
<tr>
<td>10</td>
<td>877.2</td>
<td>0.1348</td>
<td>−0.2326</td>
<td>0.004520</td>
<td>5.875</td>
</tr>
<tr>
<td>3</td>
<td>303.1</td>
<td>0.2104</td>
<td>0.005536</td>
<td>0.1529</td>
<td>4.312</td>
</tr>
<tr>
<td>7</td>
<td>737.2</td>
<td>0.1947</td>
<td>0.2388</td>
<td>0.004169</td>
<td>5.646</td>
</tr>
<tr>
<td>10</td>
<td>421.6</td>
<td>0.08324</td>
<td>0.1010</td>
<td>0.009801</td>
<td>5.517</td>
</tr>
<tr>
<td>3</td>
<td>459.5</td>
<td>0.1252</td>
<td>0.06190</td>
<td>0.01589</td>
<td>5.350</td>
</tr>
<tr>
<td>7</td>
<td>563.4</td>
<td>0.1508</td>
<td>0.08185</td>
<td>0.01207</td>
<td>5.416</td>
</tr>
<tr>
<td>10</td>
<td>392.0</td>
<td>0.07022</td>
<td>0.1101</td>
<td>0.008993</td>
<td>5.518</td>
</tr>
</tbody>
</table>
the initial concentration of the adsorbate solution. \( R_L \) values are used to describe a favorable \((0 < R_L < 1)\), unfavorable \((R_L > 1)\), irreversible \((R_L = 0)\) or linear \((R_L = 1)\) adsorption. From Table 1 we can see that most \( R_L \) values fall between 0 and 1, indicating a favorable adsorption onto our adsorbent. Interestingly, there are several \( R_L \) values which are very close to 0 which would describe an irreversible adsorption; this could be attributed to very strong adsorbate/adsorbent interactions under these conditions.

**Adsorption kinetics**

The adsorption kinetics of NTC and AC towards all three contaminants were compared and can be seen in Figure 3. Data acquired through the kinetic adsorption experiments were fitted to Lagergren-first order, pseudo-second order and intra-particle diffusion kinetic models. Furnished model details can be found in Supplemental Figure 6, with the adjusted \( R^2 \) values summarized in Supplemental Table 3. The regression values \( (R^2) \) of pseudo-second order model were considerably higher and nearer to unity than pseudo-first order model, showing better fitting of the pseudo-second order model. In addition, nearly identical calculated \( (Q_{\text{max, calc.}}) \) and experimental \( (Q_{\text{max, exp}}) \) adsorption capacity values further support the applicability of the pseudo-second order kinetic model. Intraparticle diffusion models for all three contaminants appear to show two adsorption phases, with the first phase \( (t^{0.5} \) between 0 and 2.236) demonstrating a steep positive slope, followed by a near-plateau at \( t^{0.5} \) between 2.236 and 15.49. This is indicative of more than one process governing the adsorption process of the contaminants onto our adsorbent.

**Continuous flow adsorption study**

To simulate water purification in real-world filtration systems, a continuous-flow purification system was tested (Supplemental Figure 7). Briefly, 1 g of NTC was mixed with 100 g of sand and packed into a 250 mL glass column. A 20 mg/L MB solution made in tap water was passed through this packed column via gravity filtration with a constant flow rate of 4.5 mL/min. The column was kept under constant flow until traces of MB were observed in the filtrate. Flow adsorption proved 100% efficient up to 11.5 L, with the breakthrough point at 12 L. The flow experiment was continued up to 15 L, at which point the adsorption efficiency had decreased to 72%. Under these experimental conditions, this material has the potential to purify 230 L of 1 mg/L MB-contaminated water with 100% removal efficiency.

**Comparison with other adsorbents**

Adsorption capacities and surface area of our material has been compared to similar adsorbents and can be seen in Table 2. The surface area of NTC, while not the highest, is at the higher end of the spectrum, nearly matching those of carbonized metal-organic frameworks (MOFs) which are known to have large surface areas, and more than doubling that of sulfonated graphene nanosheets. Adsorption capacities for our material at near-neutral pH either surpasses or is on-par with other materials. For MB, adsorption capacity of NTC is higher than other biomass-derived adsorbents. Adsorption of 2-naphthol is much higher than that of many organoclays, and more than doubles the \( Q_e \) reported for bamboo hydrochars and even
sulfonated graphene sheets. BPA adsorption, while not the highest, is still on-par with materials such as carbonized MOFs and activated tire adsorbents.

**CONCLUSION**

In summary, we have developed a carbon adsorbent from the carbonization of glucose at 1,000 °C under argon conditions in the presence of ZnO nanoparticles which yielded a nanotemplated porous adsorbent material with surface area of 1,228.19 m²/g and average pore diameter of 14.77 nm. From SEM-EDS we observe an elemental composition of 90.2% carbon and 8.2% oxygen, and XRD analysis indicates the presence of sp² hybridized carbons and honeycomb structures Experimental Q_max values for MB, 2-naphthol and BPA at pH 7 are 539 mg/g, 737 mg/g and 563 mg/g, respectively. Adsorption kinetic experiments demonstrate a good fit for the pseudo-second order kinetic model. We believe this method of generating adsorbent carbon materials from inexpensive starting materials can have a huge impact on the synthesis of adsorbents for water remediation of organic pollutants in the future.

**ACKNOWLEDGEMENTS**

This work was supported by the NSF ERC-1449500 Nanosystems Engineering Research Center on Nanotechnology-Enabled Water Treatment (NEWT); the USDA NIFA 2014-38422-22078 (I-DISCOVER); and the Ralph & Kathleen Ponce de Leon Endowment at UTEP. The authors would like to thank Dr Paul Westerhoff from Arizona State University and his team for their help with BET and BJH analysis.

**DATA AVAILABILITY STATEMENT**

All relevant data are included in the paper or its Supplementary Information.
REFERENCES


Han, S.-W., Jung, D.-W., Jeong, J.-H. & Oh, E.-S. 2014 Effect of pyrolysis temperature on carbon obtained from green tea biomass for superior lithium ion battery anodes. Chemical Engineering Journal 254, 597–604.


Krugly, E., Martuzevicius, D., Tichonovas, M., Jankunaite, D., Rumskaite, I., Sedlina, J., Racys, V. & Baltrusaitis, J. 2015


Rodríguez-Reinoso, F. & Molina-Sabio, M. 1992 Activated carbons from lignocellulosic materials by chemical and/or physical activation: an overview. *Carbon** 30 (7), 1111–1118.


First received 14 May 2020; accepted in revised form 14 August 2020. Available online 28 August 2020