Water Purification through a Novel Electrospun Carbon Nanofiber Membrane

Tariq Jamil, Shamsa Munir, Qamar Wali, Gul Jamil Shah, Muhammad Ejaz Khan, and Rajan Jose

ABSTRACT: Here, we report water purification through novel polyvinyl alcohol (PVA)-based carbon nanofibers synthesized through the electrospinning technique. In our novel approach, we mix PVA and tetraethyl orthosilicate (TEOS) with green tea solutions with different concentrations to synthesize carbon-based nanofibers (CNFs) and further calcine at 280 °C for carbonization. The scanning electron microscopy (SEM) results show the diameter of the nanofibers to be ~500 nm, which decreases by about 50% after carbonization, making them more suitable candidates for the filtration process. Next, using these carbon nanofibers, we prepare filters for water purification. The synthesized CNF filters show excellent performance and successful removal of contaminants from the water by analyzing the CNF-based filters before and after the filtration of water through SEM and energy-dispersive X-ray (EDX) spectroscopy. Our SEM and EDX results indicate the presence of various nanoparticles consisting of different elements such as Mg, Na, Ti, S, Si, and Fe on the filters, after the filtration of water. Additionally, the SEM results show that PVA and TEOS concentrations play an important role in the formation, uniformity, homogeneity, and particularly in the reduction of the nanofiber diameter.

1. INTRODUCTION

We have been racing against time to devise an economical and sustainable technology for water purification due to the rapid growth in population. Noteworthy is the fact that at the turn of the millennium there had been over 1 billion individuals who had no access to safe drinking water with 4000 children below the age of 5 who died because of unclean water. However, with the joint efforts of the World Health Organization and United Nations, access to clean water to a significantly large percentage of the population has improved; however, still a large number of people in the world have no access to clean and safe drinking water, especially in developing countries.1

Nowadays, many consumer products contain heavy metals, metal oxides, and non-metallic nanoparticles (NPs), the occurrence of which increases their probability to be released into natural water and generate an unhealthy environment.2 Natural water is often contaminated by nanosized inorganic materials, such as arsenic, iron, lead, mercury, copper, nickel, zinc, cobalt, silver, sodium, potassium, magnesium, and so forth, making it unsafe for consumption. It is estimated that around 1300 fiber-based products are being marketed and hence are likely to enter the aquatic systems causing health concerns due to their persistency in water systems.3

The nanofibers synthesized by the electrospinning technique have remarkable characteristics such as a large surface to volume ratio, excellent morphology, and chemical activity rendering them a suitable candidate for various applications such as sensors, composites, and for air and water purification.4 There are several polymeric fibers, including natural (silk, cotton, etc.) and synthetic (polyester, polyamide, etc.) that can be used as adsorbents for the elimination of dyes and metal ions from wastewater.5 These include fibers based on polyvinyl alcohol (PVA), polyacrylic acid, and pullulan, excellent adsorbents for Cr(VI) removal.6 FIBAN ion-exchange fibers show the best performance for water softening and removal of heavy metal ions including Cu^{2+}, Co^{2+}, Zn^{2+}, Ni^{2+}, Pb^{2+}, and Cd^{2+}.7 The composite of cotton fibers and the ZrO_{2}^+ adsorbent shows high capacity for Cr(VI) ion removal.8 The carboxyl group-containing hydrazine fibers are excellent candidates for the extraction of zinc, copper, cadmium, lead, chromium, nickel, and cobalt.9 The polyacrylonitrile (PAN)-based fiber contains a bis-amide group having significant capacity for the removal of Cu^{2+}, Co^{2+}, Zn^{2+}, Mn^{2+}, Mg^{2+}, Cr^{3+}, and Hg^{2+}.10 A poly(acrylphenyl amidrazone-phenyl hydrazide) chelating fiber showed excellent performance in the removal of V(V), Bi(III), Ga(III), Tl(IV), and In(III) from...
wastewater.\textsuperscript{11} Similarly, PAN fibers were used as an adsorbent for the extraction of copper, lead ions, and humic acid from aqueous solutions.\textsuperscript{12} A poly(acryl benzoylamidrazone-acryl-benzoyl hydrazine) chelating fiber is reported to be highly efficient for the removal of Pd(IV) and Au(III) ions from the solution.\textsuperscript{13} Polyamide fibers displayed a maximum adsorption capacity of the adsorbent for Cu\textsuperscript{2+} and Pb\textsuperscript{2+} ions.\textsuperscript{15} PAN–polyamidoamine-based nanofibers are being used for the elimination of Direct Red 80 (DR80) and Direct Red 23 (DR23) dyes.\textsuperscript{15} Composite nanofibers modified with dendrimer-coated CeO\textsubscript{2} NPs manifested remarkable efficiency to get rid of chromium and phenol.\textsuperscript{16} The N\textsubscript{6}PPI-based nanofibers displayed successful and efficient extraction of anionic AR252 organic and inorganic dyes from water.\textsuperscript{17}

Carbon nanofibers (CNFs) have attracted considerable attention in the field of water filtration, as they exhibit unique features such as high porosity, large surface to volume ratio, low density, and high flexibility.\textsuperscript{18} The fiber-based membranes have small pore sizes, low cost, and high efficiency in terms of the removal of contaminants from water.\textsuperscript{19,20} While the production of a free-standing non-polymeric nanofiber mat is still a technological challenge due to their intrinsic brittleness, large-area CNF sheets with high mechanical strength and flexibility can be easily fabricated. In addition, their higher chemical stability compared to polymeric filters makes them suitable for water filtration.\textsuperscript{21} Polyvinyl alcohol (PVA) is a semi-crystalline fiber, which in comparison with other fibers has a large carbon content (54.5\%) and easily splits the hydroxyl groups in the polymer chain that make PVA a favorable precursor for the fabrication of carbonaceous materials. So far, PVA cross-linked to cellulose nanofibers from a hybrid aerogel has been used as a superabsorbent for oils, organic solvents, and different heavy metals and, hence, are potential candidates to be used for water purification.\textsuperscript{22} Additionally, outstanding characteristics such as high mechanical strength, high flexibility, high thermal stability, and unique morphology of the PVA-based nanofibers makes them preferable over conventional nanofibers based on poly(furfuryl alcohol), polyvinylidine chloride, polyimide, PAN, polyvinylidine fluoride, and PVA.\textsuperscript{23} However, the existing PAN-based nanofibers have low performance due to laborious synthesis protocols which result in an inefficient membrane morphology with a large pore size, thereby leading to inadequate filtration.\textsuperscript{24} To overcome these issues in PAN-based CNFs, we propose the novel PVA-based CNFs, prepared through green nanotechnology and are more flexible, adhesive, and have high tensile strength as compared to CNFs based on PAN.\textsuperscript{19,25}

Electrospinning has been a pioneering technology for the production of ultra-thin membranes.\textsuperscript{26} It is very simple process, which can also be used for the fabrication of nanofibers on an industrial scale.\textsuperscript{27} Its various parameters, that is, different operating voltages, jet diameters, and the distance between the needle and the collector affect the morphology of nanofibers.\textsuperscript{28} Polyvinyl chloride was added to polyvinylpyrrolidone (PVP) using an electrospinning process with different percentages so that the surface of the nanomembrane becomes hydrophilic and gives the best performance.\textsuperscript{29} In this study, we report the development of efficient CNF membranes for the removal of toxic NPs from aqueous solutions. Free-standing CNF membranes were fabricated by electrospinning the PVA precursor solution followed by thermal treatment of the fibers. Moreover, tetraethyl orthosilicate (TEOS) was added for the flexibility and to increase the specific surface area of the CNFs.\textsuperscript{30} To the best of our knowledge, deriving CNFs from PVA/TEOS and the synthesis of the CNF filter through green nanotechnology to provide safe and healthy drinking water at affordable prices have not been reported elsewhere. Our results reveal the removal of Mg, Na, Ti, S, Si, and Fe by filtration of contaminated water through the CNF filter. Interestingly, we also find that these membranes could efficiently reject various NPs of different sizes and nature from the contaminated water due to the small size of the membrane pores. Additionally, we also present the synthesis of continuous and uniform diameter carbon nanofibers and its nanofilter. These filters are supposed to be cost-effective, portable, and can be easily installed on domestic taps and pipes, and so forth.\textsuperscript{31}

2. RESULTS AND DISCUSSION

2.1. X-ray Diffraction Analysis. Figure 1a shows the X-ray diffraction (XRD) analysis of the composite and carbonized nanofibers based on PVA/TEOS. As shown in Figure 1a, there is only one main peak, where the values of 2\(\theta\) are 22.67 and 20.48\(^{\circ}\), while the intensities recorded are 415 and 595 for the composite and carbonized nanofibers, respectively. The overall structure is amorphous as is evident from the XRD pattern.\textsuperscript{32} In carbonized nanofibers, the peaks increased, due to the arrangement of different atoms. The small amount of crystallinity in carbonized nanofibers is due to carbonization.\textsuperscript{33}

Figure 1b shows the XRD analysis of the carbonized and composite nanofibers based on pure PVA. As shown in Figure 1b, only one peak at 2\(\theta\) values of 19.61\(^{\circ}\) is observed where the intensity is recorded at 425 for the composite and two peaks at 34745

https://doi.org/10.1021/acsomega.1c05197
ACS Omega 2021, 6, 34744−34751
values 22.51 and 29.5° are observed where the intensities are recorded at 440 and 460, respectively, for carbonized fibers. Small peaks at 32.3 and 39.5° are observed in the carbonized fibers at different angles which is attributed to carbonization. \(^{34}\) The overall structure is amorphous. \(^{35}\)

### 2.2. Fourier Transform Infrared Spectroscopy Analysis

Figure 2 shows the Fourier transform infrared (FTIR) spectrum of the carbonized and composite nanofibers in the 500 to 4000 cm\(^{-1}\) range.

![FTIR pattern](image)

**Figure 2.** FTIR patterns of the carbonized and composite nanofibers in the 500 to 4000 cm\(^{-1}\) range.

The green synthesis of CNFs has been published by many researchers using a green tea extract, which is a cost-effective and domestic source. The green tea extract was preferable because of its environment-friendly nature, solubility in water at room temperature, and does not give any toxic byproducts. The green tea plant extracts are affluent in polyphenols and caffeine, which have excellent antioxidant characteristics. Hoag et al. reported the synthesis of stable nanoscale zero valent iron (nZVI) at room temperature by using a green tea extract without the addition of any surfactant or polymer. \(^{38}\) The polyphenols in green tea leaves act as a reducing agent and a capping agent, which results in stable green CNFs with unique properties. Similarly, Shahwan et al. prepared nZVI by the electrosprinning technique using a 0.10 M iron chloride solution to green tea in 2/3 volume ratios. The prepared nZVI fiber having a 40–60 nm diameter is used as a catalyst for the degradation of methylene blue and methyl orange dyes. \(^{39}\) Ponder et al., in another study, successfully, synthesized the nZVI with a diameter of 10–30 nm on a nonporous, hydrophobic polymer resin support. The synthesized nZVI shows a high reactivity toward the removal of metal-ion impurities in aqueous solution. \(^{40}\) Keeping these points in view, we employed green tea as a starting material in our study. It shows a better adsorption effect on our synthesized CNFs, as discussed in the forthcoming sections.

The peak at \(\sim 1715\) cm\(^{-1}\) is due to the C–O stretching vibration from the remaining alcoholic group in the carbonized nanofiber sample. \(^{41}\) The peak at \(\sim 1615\) cm\(^{-1}\) of the C=C stretching vibration is slightly shifted to \(\sim 1550\) cm\(^{-1}\) due to the carbonization of composite nanofibers. The peaks at \(\sim 1415\) ~\(1319, 1230, \) and \(\sim 1140\) cm\(^{-1}\) observed in the composite nanofiber spectrum have been attributed to C–O and C–C stretching vibrations which disappear after carbonization, and a flat peak at \(\sim 1350\) cm\(^{-1}\) appears due to the C–C stretching vibration. \(^{37}\) The peak at \(\sim 1110\) cm\(^{-1}\) after carbonization is ascribed to the C–C stretching vibration, which is an indication of the crystalline region in the composite nanofibers. The sharp peak at \(\sim 1110\) cm\(^{-1}\) corresponds to the Si–O–Si stretching vibration, but it is slightly shifted due to carbonization. \(^{32}\) The absorption peaks at \(\sim 872\) cm\(^{-1}\) and the less intense absorption band from \(\sim 745\) to \(\sim 620\) cm\(^{-1}\) are attributed to the characteristic vibrations of Si–O–Si and C–Si asymmetric stretching in carbonized nanofibers, respectively. \(^{43}\)

### 2.3. Morphological Analysis

#### 2.3.1. Effects of Heating on the Morphology of Nanofibers

The scanning electron microscopy (SEM) images of the composite and carbonized nanofibers are shown in Figure 3a–d. The composite nanofibers were heated overnight at 100 °C. Then, it was collected from an Al collector for carbonization. For a morphological and roughness study of the synthesized nanofibers, the samples were prepared in a powder form. Subsequently, the samples were coated with a platinum thin layer via the sputtering technique to make the surface conductive and to avoid any possible charging effect while performing SEM analysis. The coated samples were then loaded into a SEM measurement chamber under high vacuum and were examined at a high voltage of about 3–10 kV.
The SEM images of the nanofibers are taken at different resolutions of 500 nm, as shown in Figure 3a, and 1000 nm, as shown in Figure 3c. The diameters of nanofibers were almost uniform and aligned. No cracks, beads, or branches in the fiber are observed. However, the joint is due to the alignment of one fiber on another owing to a fixed collector. The diameters of the composite nanofibers reduced from 500 to 230 nm (a,b) and from 630 to 290 nm (c,d). The shrinkage in diameters of fibers is due to the decomposition of PVA and TEOS after the carbonization of composite nanofibers.44

2.3.2. Effects of PVA Concentrations on the Morphology of Nanofibers. The SEM images of the carbonized nanofibers are shown in Figure 4a–d. Upon varying the amount of PVA in the solution, the diameter of the nanofibers varies significantly. It can be seen from the SEM images that the CNFs are distributed uniformly throughout the materials and there is no agglomeration. The diameter of CNF was found to be 400 nm with the addition of 2 g of PVA, which further decreased to 350, 240, and 200 nm at 1.8, 1.6, and 1.4 g, respectively.

2.4. Carbon Nanofiber Filter Performance Tests. 2.4.1. SEM and EDX Analyses of the Filter before Filtration of Water. Figure 5 shows the SEM and energy-dispersive X-ray (EDX) analyses results of the CNF-based filter. The EDX results show the presence of elements; C, O, Al, and Si. Due to the carbonization of fibers, the quantity of carbon has increased. The presence of oxygen is due to the surface oxidation nanofibers in air during handling. The Al is due to the use of a collector in electrospinning.

2.4.2. SEM and EDX Analyses of the Filter after Filtration of Water. Figure 6 shows the SEM and EDX images of the CNF filter after filtration of water, in which the contaminated particles are clearly shown. The CNF filter trapped the contaminated particles and purified the water. The overall morphology of fibers is the same as before; however, now the contaminated particles appeared on the fibers, as shown in Figure 6. The presence of oxygen is due to the surface oxidation of nanofibers in air during handling. Furthermore, the results showed the presence of some other elements, that is, Mg, Na, Ti, S, Si, and Fe. These elements are due to the contaminated water which appeared on the filter after the process of filtration. This was also confirmed by the SEM image of the filter (Figure 6b). The quantity of Si has also increased due to the silica present in contaminated water. Thus, our post-filtration analysis of CNFs clearly revealed the removal of contaminations to purify the water.

3. EXPERIMENTAL SECTION

3.1. Materials. The synthesis of carbon nanofibers involves two major steps: first is the preparation of the solution and second is electrospinning. In solution preparation, green tea (GT, locally available), PVA (Mw = 66,000, Junsei), and TEOS (98% purity, Sigma-Aldrich) were used. PVA and GT were used as precursor materials. TEOS was added for the flexibility and to increase the specific surface area of the CNFs. In solution preparation, GT (150 g) and distilled water (20 mL) were mixed. The mixed solution was then heated at 100 °C for 20 min. The GT solution was filtered through the silicon filter and the filtered solution was heated at 100 °C for 30 min again. Then, PVA (1.4 g) was mixed with the GT solution and stirred for 45 min at 500 rpm. When the PVA and GT had been mixed thoroughly, then TEOS (0.6 mL) was mixed with it. The concentration of the prepared solution was 1.589 mol/L. Then, the solution was stirred for 3.0 to 5.0 h to make the desired viscosity of the solution.

The whole process during the solution preparation is shown in the block diagram, as shown in Figure 7a. Electrospinning was used for the synthesis of carbon nanofibers. It is the second most important step for the preparation of CNFs. The basic principle of this technique is electrostatic forces. In this work, we used the electrospinning setup, which operates on 17 kV. An 18 mm gauge needle was used. The distance between the collector and the needle was 10 in. The composite nanofibers dried overnight at 100 °C in an oven (Thomas Scientific Model, 605) and then collected from aluminum foil. These dried nanofibers were kept in a tube furnace (Nabertherm Model, LHT 04/18) at 280 °C for 5 h with a 3 °C/min rise in temperature within the air atmosphere. For carbonization at 700 °C for 2 h in a nitrogen atmosphere with a heating rate of 3 °C/min, the organic contents were evaporated and PVA was pyrolyzed to carbon, and through this CNFs were obtained.3,4 After synthesis of CNFs they are used as a filter for the purification of dusty water. The wastewat was collected from the local river in which many houses and industries’ wastewater was mixed. In the purification procedure, we take a strip of CNFs and put it on a beaker. Wee attached CNFs to the beaker with the help of tape so that the CNF strip does not fall into the beaker with water. In this way, we smoothly filtered the wastewater through the CNF strip. The CNF strip, that is, the filter was analyzed, through SEM and EDX before and after the filtration of wastewater in order to clarify the purification function of CNFs. In Figure 7b, the whole procedure is shown.

3.2. Characterization Techniques. The crystallinity of the composite and carbonized nanofibers was investigated through a powder X-ray diffractometer (Rigaku Miniflex II X-ray diffractometer, Ni-filtered Cu Kα radiation, λ = 1.5406 Å). For morphological and roughness studies of the synthesized nanofibers, the sample was prepared in the powder form. Subsequently, the samples were coated with a platinum thin layer via a sputtering technique to make the surface conductive and to avoid any possible charging effect while performing SEM analysis. The coated samples were then loaded into the SEM measurement chamber under high vacuum and were
Figure 5. SEM and EDX results of the CNF filter before filtration: (a) at 10 μm resolution and (b) at 5 μm resolution.

Figure 6. SEM and EDX results of the CNF filter after filtration: (a) at 10 μm resolution and (b) at 5 μm resolution.
examined at a high voltage of about 3–10 kV. The morphology was examined using a scanning electron microscope (JSM-5910 JEOL Japan). IR transmission spectra were collected in the range of 400–4000 cm⁻¹ using a PerkinElmer Spectrum Two FTIR spectrometer, equipped with a universal attenuated total reflection accessory. An EDX electron spectrometer (INCA 200, Oxford Instruments, UK) was used for elemental analysis and their compositions.

4. CONCLUSIONS

CNFs were successfully synthesized via the electrospinning technique for water purification and filtration. The synthesized CNFs were characterized via XRD, FTIR, SEM, and EDS analyses. The XRD results showed that the CNF structure is amorphous in nature; however, a small crystallinity was observed after carbonization. The SEM analysis confirmed that the diameter of CNFs was in the range of 500 nm, which further decreased to almost 50% thereby resulting in the reduction of the pore size and making it more suitable for the filtration process. The SEM analysis revealed that different concentrations of PVA and variable parameters of the electrospinning setup affect the morphology of nanofibers. Finally, the CNF filter was successfully synthesized. The SEM and EDX analyses showed excellent filtration results, clearly indicating the removal of contamination and purification of water.

Figure 7. (a) Schematic of the solution preparation and electrospinning setup. (b) Water purification process, (c) top view of the purification process, and (d) water before and after filtration.

AUTHOR INFORMATION

Corresponding Author
Shamsa Munir – School of Applied Sciences & Humanities, National University of Technology, 44000 Islamabad, Pakistan; orcid.org/0000-0003-2483-5179; Email: smunir@nutech.edu.pk

Authors
Tariq Jamil – Faculty of Engineering Science, Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, 23460 Topi, Khyber Pakhtunkhwa, Pakistan
Qamar Wali – School of Applied Sciences & Humanities, National University of Technology, 44000 Islamabad, Pakistan
Gul Jamil Shah – Pakistan Navy Engineering College, National University of Science and Technology, 44000 Islamabad, Pakistan
Muhammad Ejaz Khan – Department of Computer Engineering, National University of Technology, 44000 Islamabad, Pakistan
Rajan Jose – Nanostructured Renewable Energy Materials Laboratory, Faculty of Industrial Sciences & Technology, 26300 Kuantan, Pahang, Malaysia; orcid.org/0000-0003-4540-321X

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.1c05197

Notes
The authors declare no competing financial interest.

Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article [and/or] its Supporting Information.

ACKNOWLEDGMENTS

The authors acknowledge the National University of Technology (NUTECH), Islamabad, for providing laboratory and space facilities.

REFERENCES

(1) WHO. Progress on Sanitation and Drinking Water: 2015 Update and MDG Assessment, 2015.
(2) (a) Adeleye, A. S.; Conway, J. R.; Garner, K.; Huang, Y.; Su, Y.; Keller, A. A. Engineered nanomaterials for water treatment and remediation: Costs, benefits, and applicability. Chem. Eng. Sci. 2016, 286, 640–662. (b) Leonard, P.; Hearty, S.; Brennan, J.; Dunne, L.; Quinn, J.; Chakraborty, T.; O’Kennedy, R. Advances in biosensors for detection of pathogens in food and water. Enzyme Microb. Technol. 2003, 32, 3–13.
(3) Brayner, R. The toxicological impact of nanoparticles. Nano Today 2008, 3, 48–55.
(4) He, H.-J.; Liu, C.-K.; Molnar, K. A novel needleless electrospinning system using a moving conventional yarn as the spinneret. Fibers Polym. 2018, 19, 1472–1478.
(5) (a) Razzaz, A.; Ghorban, S.; Hosayni, L.; Irani, M.; Aliabadi, M. Chitosan nanofibers functionalized by TiO2 nanoparticles for the removal of heavy metal ions. J. Taiwan Inst. Chem. Eng. 2016, 58, 333–343. (b) Hua, M.; Zhang, S.; Pan, B.; Zhang, W.; Lv, L.; Zhang, Q. Heavy metal removal from water/wastewater by nanosized metal oxides: a review. J. Hazard. Mater. 2012, 211, 317–331. (c) Haji, A. Modified textile fibers for waste water treatment. Environ. Eng. Sci. 2016, 4, 327–353.
(6) Mousavi, S.; Shahrazi, F.; Aliabadi, M.; Haji, A.; Deuber, F.; Adlhart, C. Surface enriched nanofiber mats for efficient adsorption of Cr (VI) inspired by nature. J. Environ. Chem. Eng. 2019, 7, 102817.
Silva Alfaya, R. V.; da Silva Alfaya, A. A. Cotton fiber/ZrO2, a new water and application for the removal of heavy metals. ACS Omega http://pubs.acs.org/journal/acsodf and 2011, 52, 234–258.

(25) Faccini, M.; Borja, G.; Boerrigter, M.; Morillo Martín, D.; Martínez Crespiera, S.; Vázquez-Campos, S.; Aubouy, L.; Amantia, D. Electrop spun carbon nanofiber membranes for filtration of nanoparticles from water. J. Nanomater. 2015, 2015, 247471.

(26) (a) Wali, Q.; Fakhruddin, A.; Ahmed, I.; Ab Rahim, M. H.; Ismail, J.; Jose, R. Multiporous nanofibers of SnO2 by electrospinning for high efficiency dye-sensitized solar cells. J. Mater. Chem. 2014, 2, 17427–17434. (b) Bakr, Z. H.; Wali, Q.; Ismail, J.; Elumalai, N. K.; Uddin, A.; Jose, R. Synergistic combination of electronic and electrical properties of SnO2 and TiO2 in a single SnO2-TiO2 composite nanofiber for dye-sensitized solar cells. Electrochim. Acta 2018, 263, 524–532. (c) Bakr, Z. H.; Wali, Q.; Yang, S.; Yousefsadeh, M.; Padmasree, K. F.; Ismail, J.; Ab Rahim, M. H.; Yusoff, M. M.; Jose, R. Characteristics of ZnO–SnO2 Composite Nanofibers as a Photoanode in Dye-Sensitized Solar Cells. Ind. Eng. Chem. Res. 2019, 58, 643–653. (d) Wali, Q.; Bakr, Z. H.; Manshor, N. A.; Fakhruddin, A.; Jose, R. SnO2–TiO2 hybrid nanofibers for efficient dye-sensitized solar cells. Sol. Energy Mater. Sol. Cells 2016, 132, 395–404. (e) Huang, Z.–M.; Zhang, Y.–Z.; Totak, M.; Ramakrishna, S. A review on polymer nanofibers by electrospinning and their applications in nanocomposites. Compos. Sci. Technol. 2003, 63, 2223–2253.

(27) Ramaseshan, R.; Sundarrajan, S.; Jose, R.; Ramakrishna, S. Nanostructured ceramics by electrospinning. J. Appl. Phys. 2007, 102, 111101.

(28) (a) Saleh, E. J.; Mohamad Ashry, J.; Muhammad, H.; Rajan, J. A Review of Process Parameters and Morphology of HTS YBCO by Electrospinning Technique. Proceedings of the National Conference for Postgraduate Research (NCON-PGR 2016) 2016. (b) Zheng, S.; Chen, H.; Tong, X.; Wang, Z.; Crittenden, J. C.; Huang, M. Integration of a Photo-Fenton Reaction and a Membrane Filtration using CS/PAN@FeOOH@g-CN4Electrospun Nanofibers: Synthesis, Characterization, Self-cleaning Performance and Mechanism. Appl. Catal. 2021, 281, 119519.

(29) Faccini, M.; Borja, G.; Boerrigter, M.; Morillo Martin, D.; Martinez Crespiera, S.; Vazquez-Campos, S.; Aubouy, L.; Amantia, D. Electrop spun Carbon Nanofiber Membranes for Filtration of Nanoparticles from Water. J. Mater. Chem. A 2015, 2015, 247471.

(30) Jing, H. Nano scale devices: Fabrication, actuation, and related fluidic dynamics. Ph.D. Thesis, University of North Carolina at Chapel Hill, 2006.

(31) Ayoob, S.; Gupta, A. K.; Bhat, V. T. A conceptual overview on sustainable technologies for the defluoridation of drinking water. Crit. Rev. Environ. Sci. Technol. 2008, 38, 401–470.

(32) Sourav, S. Preparation of hybrid scaffold based on PVA and bioactive glass ceramics. B.Tech. Thesis, National Institute of Technology Rourkela, 2014.

(33) (a) Ma, X.; Yuan, C.; Liu, X. Mechanical, microstructure and surface characterizations of c2o2 carbon fibers prepared from cellulose after liquefying and curing. Materials 2014, 7, 75–84. (b) Alarifi, I.; Alharbi, A.; Khan, W.; Swindle, A.; Asmatulu, R. Thermal, electrical and surface hydrophobic properties of electros spun polycrylonitrile nanofibers for structural health monitoring. Materials 2015, 8, 7017–7031.

(34) (a) Yue, X.; Feng, S.; Li, S.; Jing, Y.; Shao, C. Bromopropyl functionalized silica nanofibers for effective removal of trace level dieldrin from water. Colloids Surf., A 2012, 406, 44–51. (b) Dhakate, S. R.; Chaudhary, A. G.; Gupta, A.; Pathak, A. K.; Singh, B. P.; Subhedar, K. M.; Yokozeki, T. Excellent mechanical properties of carbon fiber semi-aligned electros spun carbon nanofiber hybrid polymer composites. RSC Adv. 2016, 6, 36715–36722.

(35) (a) Sharma, R.; Rao, D. S.; Vankar, V. Growth of nanocrystalline β-silicon carbide and nanocrystalline silicon oxide nanoparticles by sol gel technique. Mater. Lett. 2008, 62, 3174–3177. (b) Guan, Y.; Hong, Y.; Shen, S.; Zhihong, T.; Dengguang, Y.; Quinlan, J. A.; Ruoff, R. S. Mechanical and structural characterization of electros spun PAN-derived carbon nanofibers. Carbon 2005, 43, 2175–2185. (c) Liu, Y.; Kumar, S. Recent progress in fabrication, structure, and properties of carbon fibers. Polym. Rev. 2012, 52, 234–258.
Junhe, Y. Preparation and dispersity of carbon nanospheres by carbonizing polyacrylonitrile microspheres. RSC Adv. 2017, 7, 16341–16347.

(36) Wang, T.; Jin, X.; Chen, Z.; Megharaj, M.; Naidu, R. Green synthesis of Fe nanoparticles using eucalyptus leaf extracts for treatment of eutrophic wastewater. Sci. Total Environ. 2014, 466, 210–213.

(37) Dirican, M.; Yanılmaz, M.; Fu, K.; Yıldız, O.; Kızıl, H.; Hu, Y.; Zhang, X. Carbon-confined PVA-derived silicon/silica/carbon nano-fiber composites as anode for lithium-ion batteries. J. Electrochem. Soc. 2014, 161, A2197.

(38) Hoag, G. E.; Collins, J. B.; Holcomb, J. L.; Hoag, J. R.; Nadagouda, M. N.; Varma, R. S. Degradation of bromothymol blue by ‘greener’ nano-scale zero-valent iron synthesized using tea polyphenols. J. Mater. Chem. 2009, 19, 8671–8677.

(39) Shahwan, T.; Abu Sirriah, S.; Nairat, M.; Boyaci, E.; Erögü, A. E.; Scott, T. B.; Hallam, K. R. Green synthesis of iron nanoparticles and their application as a Fenton-like catalyst for the degradation of aqueous cationic and anionic dyes. Chem. Eng. Sci. 2011, 72, 258–266.

(40) Ponder, S. M.; Darab, J. G.; Bucher, J.; Caulder, D.; Craig, I.; Davis, L.; Edelstein, N.; Lukens, W.; Nitsche, H.; Rao, L.; Shuh, D. K.; Mallouk, T. E. Surface chemistry and electrochemistry of supported zerovalent iron nanoparticles in the remediation of aqueous metal contaminants. Chem. Mater. 2001, 13, 479–486.

(41) Mansur, H. S.; Sadahira, C. M.; Souza, A. N.; Mansur, A. A. P. FTIR spectroscopy characterization of poly (vinyl alcohol) hydrogel with different hydrolysis degree and chemically crosslinked with glutaraldehyde. Mater. Sci. Eng., C 2008, 28, 539–548.

(42) Zhu, Q.; Chu, Y.; Wang, Z.; Chen, N.; Lin, L.; Liu, F.; Pan, Q. Robust superhydrophobic polyurethane sponge as a highly reusable oil-absorption material. J. Mater. Chem. 2013, 1, 5386–5393.

(43) Ghouri, Z. K.; Barakat, N. A.; Alam, A. M.; Park, M.; Han, T. H.; Kim, H. Y. Facile synthesis of Fe/CoO2-doped CNFs and their capacitance behavior. Int. J. Electrochem. Sci. 2015, 10, 2064–2071.

(44) Endo, M.; Kim, Y. A.; Hayashi, T.; Yanagisawa, T.; Muramatsu, H.; Ezaka, M.; Terrones, H.; Terrones, M.; Dresselhaus, M. S. Microstructural changes induced in “stacked cup” carbon nanofibers by heat treatment. Carbon 2003, 41, 1941–1947.

(45) Ştefănescu, M.; Stoia, M.; Ştefănescu, O.; Davidescu, C.; Vlase, G.; Şirloaia, P. Synthesis and characterization of poly (vinyl alcohol)/ethylene glycol/silica hybrids. Thermal analysis and FT-IR study. Rev. Roum. Chim. 2010, 55, 17–23.