Silica Fiber-based Visible Colorimetric Method for On-site Naphthalene Detection

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Abstract

Polycyclic aromatic hydrocarbons (PAHs) are organic compounds composed of multiple aromatic rings resulting from oil spills and industrial pollution, many of which are capable of causing long-term health damage. These chemicals, a large class of uncharged non-polar organic compounds comprised of two or more condensed benzene rings arranged in various configurations, are partially soluble in water and are particularly harmful to aquatic ecosystems. Herein we demonstrate the first nanofibrous polymer-based on-site...
colorimetric sensor for the detection of PAHs at environmentally-relevant concentrations. Electrospinning is used to create silica nanofibers, which are necessary as a reaction substrate and provide both hydrophobicity as well as support for the colorimetric reaction to occur. The volatile PAHs are concentrated in the vapor phase via a shift in the vapor-liquid equilibrium, allowing for a more sensitive detection range than in the liquid phase. Formaldehyde, under acidic conditions, is used to colorimetrically detect the PAHs—reacting to form brown quinoid compounds on top of the white silica fiber mat. Image analysis is further used to quantify the PAH concentration based off the intensity of the color change. This robust and portable sensor is an uncomplicated alternative to the traditional, expensive analytical equipment (HPLC, GC-MS), and allows for on-site and rapid water monitoring.

**Keywords:** Nanofiber, Sensor, Water, PAH
1 Introduction

As the world continues to urbanize and industrialize, pollution is of increasing concern, particularly in our water sources. While there are many classes of pollutants, a notable type is polycyclic aromatic hydrocarbons (PAHs). PAHs typically enter the environment via petrogenic processes—i.e., oil production/oil spills—and pyrogenic processes—i.e., combustion, including volcanic eruptions, forest fires, and industrial plants[1]. PAHs resulting from oil spills and industrial pollution are of particular concern to the Mississippi Sound and Mississippi-Alabama Gulf Coast areas, as these areas represent a critical nexus of food-energy-water for the region and the greater United States. PAHs are regulated by the U.S. Environmental Protection Agency (USEPA) in air, soil, and water[2]. Since PAHs have been found to cause adverse health effects, are probable carcinogens and mutagens, and are toxic to aquatic life[2–4], many are limited by USEPA to a maximum contaminant level (MCL) 0.0008 mg/L (0.8 ppb) in drinking water[2], however, in the US, some regional PAH limits are lower. For aqueous environments, one large and well-known release of PAHs was the Deepwater Horizon oil spill, which released an estimated twenty-one million kilograms of PAHs into the ocean[5], with concentrations reaching single digit ppm levels[6] and continuing to release over many years from submerged oil mats and balls[7]. Hence, simple, robust, and rapid testing methods need to be developed to determine PAH levels on-site with high selectivity and sensitivity. Structures of well-known and common PAHs are shown in Figure 1, however there exist many possible configurations of fused aromatic rings, As the International Agency for Research on Cancer as well as the World Health Organization have classified naphthalene as a probable carcinogen[8]. Many PAHs are detrimental to aquatic life as well, for example, the LC50 of C. reticulata, a small aquatic crustacean, for benzo[a]pyrene is 4.3 µg/L (ppb)[9].

![Fig. 1 Structures of PAHs: naphthalene, anthracene, and benzo[a]pyrene](image-url)

It is necessary to detect and quantify concentrations of PAHs in water sources in order to continue ensuring compliance with EPA drinking water regulations, as conventional drinking water treatment processes are largely ineffective for PAHs[10]. It is necessary to detect and quantify PAH concentrations to satisfy the rigorous requirements of potable water, monitoring groundwater contamination and remediation, and ensuring the health of our aquatic ecosystems, whose marine Living Planet Index (LPI), a metric developed by the World Wildlife Foundation which is determined by trends in 5,829 different measured marine species populations, has seen a 52% decline between 1970-2012[11]. Traditionally, analytical chemistry techniques are implemented in order to detect and quantify PAHs in samples; these techniques...
include high-performance liquid chromatography with fluorescence detectors (HPLC-FLD) and gas chromatography with mass spectroscopy (GC/MS)[12–14]. These highly sensitive methods have many limitations, however, including the high cost for sample analysis, the need for a skilled operator, and samples which may only be analyzed in laboratories, thus delaying the data as well as allowing for the possibility of contamination, evaporation, or mislabeling. Herein, we describe a colorimetric sensor for the detection of PAHs for rapid on-site determination of PAH concentration which is reliant on a silica nanofiber (Si NF) mat. The Si NF mat acts as both a preconcentration mechanism where its hydrophobicity restricts the transport of volatilized water across the mat, thus increasing our analyte concentration for more favorable kinetics, and as a reagent for the formation of brown quinoids whose colorimetric intensity can be measured versus the concentration of PAHs to calibrate our sensor. The presence of silica is necessary for the formation of the brown quinoids whose presence we can use to colorimetrically quantify the amount of naphthalene present in a sample. This Si NF mat is formed by electrospinning, a well-used process utilized to form polymeric nanofibers by applying a voltage bias to a polymer solution as it is fed out of a syringe pump. While silica may not typically be used in its polymeric form, its unique properties and the kinetics of the Stöber process allow for the formation of a silica gel polymer network which can be electrospun for a short duration of time. The Stöber process, which is the most commonly utilized wet synthesis method to form silica nanoparticles, proceeds by a tetraethylorthosiloxane (TEOS) precursor which is hydrolyzed using ethanol and a base to produce silanol monomers, where the ethoxyl groups are replaced with silanol groups. These silanol groups can then undergo condensation to generate branched siloxane clusters[15], forming a “polymeric” network of interconnected siloxane “monomers.” It is during this time before these siloxane networks begin to nucleate to form the silica nanoparticles, that the solution has the cross-linking and viscoelastic properties necessary to electrospin and form our Si NF mat which can be used for the detection and concentration of PAHs. It is the unique tetravalence combined with the polarity of Si-O bonds which allows for the silica network to have the solution properties necessary to form a nanofibrous material despite not being a conventional polymer. The specific PAH evaluated in this work was naphthalene, a two-membered PAH. The sensor apparatus consists of a heated scintillation vial with a silica nanofiber (Si NF) mat that acts as a substrate for the colorimetric reactions. Naphthalene is more volatile than the water molecules and thus, when heated, concentrate in the headspace above the solution. The mass flux equations for the evaporation of low-solubility contaminants from water developed by Mackay and Leinonen were used to estimate the evaporation of PAHs from a water solution over time. The mass flux of PAHs (Ni) across the phase boundary is described as:

\[ N_i = K_i \cdot L \cdot \left( C_i - \frac{P_i}{H_i} \right) \]

in mol/m3 h, where KiL is the overall liquid mass transfer coefficient (m/h), Ci is the bulk liquid concentration (mol/m3), Pi is the partial pressure (atm), and Hi is the Henry’s law constant (atm m3/mol). Combining the mass flux equation with an unsteady state mass balance leads to a differential equation expressing the change in concentration over time:

\[ \frac{dC_i}{dt} = -K_{il} \cdot \frac{C_i - \frac{P_i}{H_i}}{L} \]
Integrating this equation using the boundary condition $C_{i0}$ for the concentration at time zero, yields:

$$C_i = \frac{P_i}{H_i} + (C_{i0} - \frac{P_i}{H_i})e^{-\frac{x_i t}{L}}$$  \hspace{1cm} (3)

for concentration of PAH as a function of time. The aforementioned equations describe the first stage of the preconcentration technique, based on manipulation of the PAH: water equilibrium in the vapor phase of the system. Using these equations, the theoretical concentration of PAH in the vapor and liquid phases is determined to be a function of time at a desired temperature. This allows for the colorimetric detection of the PAHs in the water sample. Due to the less volatile nature of larger molecular weight PAHs, it is possible that a vacuum can be pulled to reduce the atmospheric pressure within the liquid sample container.

Fig. 2 The reaction between the sensor apparatus and naphthalene to form the para-quinone compounds responsible for the color change.

The detection chemistry shown above in Figure 2 relies on a condensation reaction of the PAH compounds with formaldehyde and sulfuric acid. This chemistry, employed in mining applications for the detection of aromatic compounds[16], generates brown colored quinoid compounds. This color change is visible with the naked eye and does not rely on fluorescence or other techniques to detect a change; only relying on image analysis (ImageJ) to determine specific concentrations of total PAH concentration. While Naphthalene is the PAH experimentally detected here, the reaction is not selective to any particular PAH. Thus, in an environmental sample, the colorimetric sensor would determine the total PAH concentration, which is the metric that the EPA uses to test water quality. The Si NF mat is necessary because of the high surface area for the reaction to take place, and it allows for the diffusion of the PAHs from the water sample to increase contact area with the colorimetric reactants. The hydrophobicity of the Si NF mat allows for the separation of PAH analyte from any volatile water. As the Si NF mat is initially white, the color change from white to brown is easily discernible. An overall schematic representation of the sensor can be seen in Figure 3.

2 Materials and Methods

2.1 Reagents and Materials

All polymers, reagents, and solvents were used as received without further alteration or purification. These include: TEOS (tetraethyl orthosilicate; Purity 99%: Alfa Aesar), Ethanol (200 proof: EX0276-4 Millipore), pure water, HCl (hydrochloric acid; 1.0 N: VWR), naphthalene (EM8.20846.1000: VWR), formaldehyde (37% in aqueous solution stabilized, 97064-606: VWR), and sulfuric acid (2.5N: VWR).
2.2 Silica Mat Electrospinning

A silica solution was prepared using TEOS, ethanol, water, and HCl with a molar ratio of 1:2:2:0.01, respectively. The TEOS and ethanol were first added to a beaker. Separately, the HCl and water were added to a second beaker and stirred vigorously. The HCl solution was added drop-by-drop to the TEOS/Ethanol solution under vigorous stirring (400 rpm). Then the solution was heated to 80 °C, left uncovered, and the stirring was continued at 400 rpm until the solution reached approximately 40% of its original volume [17]. The solution was then allowed to sit for 3-5 days before spinning in order for the polymeric silica network to form and the solution to reach a viscosity at which it could be electrospun. The silica solution was then electrospun onto an aluminum foil covered rotating drum collector. Electrospinning parameters for the silica solution were a voltage of 29 kV, a syringe pump flow rate of 3.0 mL/h, a collector drum speed of 200 rpm, a collector horizontal stroke speed of 10 mm/s, and a 200 mm distance from the needle tip to the collector surface. The electrospinning process ran for a total of 2 hours to form an adequately substantial mat (0.80 mm thick) for the colorimetric reaction substrate. Running conditions were 21 °C, with 59% relative humidity. The silica was collected as a flat sheet of NFs and placed in a dry storage unit.
2.3 Physical Characterization of the Silica NF Mat

Scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) were performed on a JEOL 7000 FE-SEM operating at 5 kV and 2.67 kV, respectively. All SEM samples were sputter-coated in a gold/palladium (Au/Pd) alloy for 1.5 min. Fiber diameter analyses were adopted from former methods. Briefly, the NIH software ImageJ (available on all platforms at: https://imagej.nih.gov/ij/) was utilized with DiameterJ (available on all platforms at: https://imagej.net/DiameterJ) to determine the fiber diameter distribution. Thermal characterization was performed using a PerkinElmer STA8000, where the fibers were raised from a starting temperature of 25 ºC to 900 ºC at a rate of 4 ºC per minute under constant inert nitrogen gas. A Kino model SL200KS goniometer was utilized to determine the hydrophobicity of the silica mat via contact angle measurement.

2.4 Colorimetric Sensor Evaluation

To begin the colorimetric sensor evaluation, solutions spiked with naphthalene were used to evaluate the response of the sensor. Samples ranging from 0.01 ppm to 336 ppm naphthalene with 20 mL of water were created and utilized for testing. The testing itself was performed with the use of a 20 mL scintillation vial, a fabricated holder for the system, and the silica NF mat. The fabricated holder consists of two Teflon blocks. The bottom block attaches to the top of the scintillation vial and has a drilled hole 2 mm in diameter that leads the naphthalene vapors to the silica NF mat. The top block has a 2 cm diameter hole drilled in it, and rests on top of the silica mat to hold it in place. The 2 cm hole allows for the addition of the reagents and to see the color change that occurs on the surface of the mat. The outside of the two blocks are wrapped with adhesive tape to fasten them together as well as prevent vapor volatilized from the sample from escaping. The water sample was loaded into the scintillation vial; then, the vial was heated to 80 ºC with a temperature-controlled oil bath. Formaldehyde and sulfuric acid were added in 100 µL increments via a pipette to the top of the silica NF mat to enable the colorimetric reaction to occur. 3 drops of sulfuric acid were added then 2 drops of formaldehyde. After a minute, the color change had fully developed. Photographs, taken by a smart-device, were taken of the sensing apparatus and analyzed for the colorimetric image intensity.

2.5 Image Intensity Analysis

Briefly, the NIH software ImageJ (available on all platforms at: https://imagej.nih.gov/ij/) was utilized to determine the color intensity of the brown color change regions of the silica NF mat. First, the distinct color change region (with a standard number of pixels) was selected, then inverted, and the mean color intensity was obtained from the software’s histogram output. Only the color change region is selected in order to increase signal to noise ratio, giving more accurate readings of color intensity. This intensity was then correlated to the concentration of the PAHs in the aqueous samples to develop a calibration curve[18]. An example is shown in Figure 4.
3 Results and Discussion

3.1 Physical Characterization of Silica Fibers

For the silica NF mat, a characteristic SEM image is shown in Figure 5. The average fiber diameter was found to be $850 \pm 22$ nm, after examining 10 SEM micrographs of fibers similar to Figure 5 using the DiameterJ plugin for ImageJ. It can be seen that the surfaces of the fibers are smooth, and the diameters are highly uniform and consistent.

Utilizing the ImageJ measure function, the void fraction of Figure 5 was found to be 0.51972, indicating a high fractional free volume to allow for the transport of the PAH analytes through the silica NF mat where they can react with the reagents on top. EDX analysis (Figure S1) showed a high intensity K $\alpha$ peak at 1.739 indicating silicon, along with minor peaks. A second major peak was shown at 0.525, indicating the K $\alpha$ peak of oxygen. The normalized atomic percents of silicon to oxygen after baseline correction as well as accounting for detected gold (the result of sputter coating) was calculated to be 33% to 66%, respectively. This is in agreement with the oxidation state of the predicted SiO$_2$ NFs. This can be used to calculate values of 53 wt% oxygen and 47 wt% silicon. Due to the fact that the nanofibers are reagents in the formation of the brown quinoids, and the original precursor solution used to electrospin them is composed of TEOS and contains no silica, it is necessary to verify that the Stöber process[19, 20] to form silica occurs and that the fibers are made of silica. Fourier transform infrared spectroscopy (Figure 6) strongly suggested that the fibers were composed of silica by having its most predominant peak at 1068 cm$^{-1}$ — representative of Si – O stretching bond, with an attached peak at 1202 cm$^{-1}$ — 1) represents Si –
OH stretching as a result of ethoxysilanol formation during the Stöber reaction which did not undergo the final condensation reaction. This indicates C−OH bending from either residual ethyl alcohol within the electrospun precursors solution, or ethanol that is formed during electrospinning. The residual solvents are shown to have no effect on the colorimetric mechanism for PAH detection, as the brown quinoids form regardless in the presence of the ethyl alcohol and the ethoxysilanol.

Fig. 5 FTIR analysis of silica fibers that shows the formation of silica nanofibers.

Once it was confirmed that the electrospinning process created smooth fibers that allow for the transport of naphthalene across the mat, and the composition of these fibers was established, it could be reasonably assumed that the colorimetric reaction could occur with these fibers. The hydrophobicity of these fibers, however, plays a key role in preventing water from diffusing through the NF mat, allowing the PAH analytes to increase in concentration as they diffuse through the NF mat, allowing the PAH analytes to increase in concentration as they are not diluted by the excess water. To test the hydrophobicity of the fiber mats, water contact angle goniometry was utilized. Goniometry was performed using the photograph (Figure 7) of water being dropped onto the silica nanofibers, where the contact angle could then be taken. The measured contact angle was 103° after ten minutes on the fibers, the same time it takes for a run of the fabricated sensor to occur. This illustrates the stability of the hydrophobicity of the fibers for the proposed sensor application.

With the silica nanofiber mat also playing a role in the colorimetric reaction chemistry of the sensor, it is imperative that the silica nanofibers will not decompose at the 80 °C temperature that is required to move the naphthalene through them. To ensure that the electrospun fibers are stable at these temperatures, as well as comparison against other silica TGA/DSC experiments. The fibers underwent TGA and DSC thermal characterization. The results of the experiment can be seen below in Figure 8.
Fig. 6  Contact angle measurement of water on the electrospun silica fibers. A contact angle of 90° or higher indicates that the nanofiber substrate is hydrophobic.

Fig. 7  Results of thermal characterization experiments of electrospun silica nanofibers.

The TGA data of the silica nanofibers aligns as expected with other high surface area to volume ratio thermally characterized silica samples such as felts and other electrospun fiber samples[23, 24]. The first decrease in overall weight percent corresponds to water loss as well as excess ethanol solvent that may not have evaporated during the electrospinning process leading to its collection on the nanofibers. Further weight loss occurs as more water is formed and then consequently evaporated as a result of the silanol groups undergoing self-condensation reactions[25]. The slight uptick in weight percent at the end of the experiment is
a result of the shift in crystalline structure that occurs as silica transforms into an amorphous crystalline solid at approximately 600 °C and then into a more crystalline quartz structure as it approaches 900 °C[26]. As the initial changes in weight are a result of solvent evaporation, the silica nanofiber mat will be sufficiently stable to undergo the brown quinone forming reaction which serves as the basis of this portable and inexpensive colorimetric sensor.

3.2 Visible Colorimetric Sensor Evaluation for Detection of PAHs

The silica NF mat was then evaluated as a device for the detection of PAHs in aqueous water samples. Naphthalene, a two-membered aromatic ring structure, was chosen as the model PAH, as it is the simplest of all PAH compounds and typically the most abundant PAH as a result of oil spills [27]. As a result, naphthalene is likely present if other larger PAH structures are found within the environment. An initial calibration curve relating the mean color intensity obtained from image analysis to the naphthalene concentration can be seen in Figure 8.

![Fig. 8 Calibration curve for sensor relating the obtained colorimetric signal (which can be a minimum of 0 to a maximum of 255) to the naphthalene concentration (ppm). A decrease in the colorimetric signal with a decrease in naphthalene concentration is observed.

While standard deviations at some naphthalene concentrations may overlap, this simply represents variance in the data, which could likely be minimized via sensor optimization. The coefficient of determination is 0.80576 which shows a clear positive correlation between the increase in naphthalene concentration and an increase in colorimetric intensity of the sensor, thus proving the concept of the sensor. These can largely be attributed to outliers in the data and will likely decrease as more data is collected. We can confirm this by removing outliers that are beyond a certain standard deviation from the average. By removing data points that are more than one standard deviation away from the mean colorimetric intensity of their
concentration, the R^2 value increases to 0.9099, as the new calibration curve without these outliers then accounts for 90.99% of the data. After statistical analysis utilizing an F-test, our significance value, f, was calculated to be as low as 5.64(10^{-6}), meaning that there is a less than 0.000006% chance statistically that our sensor’s current calculated calibration curve can be proven to inadequately reflect the data collected, outliers and all. Other common statistical analysis methods for chemical sensor data such as cross validation show auspicious results. A training set of data was chosen by randomly picking one data point from each naphthalene concentration. These points were fitted to predict the validation set of the other data points. After a prediction model from those points was created, it was used to find a calculated expected estimate of colorimetric intensity at each concentration. The furthest residual from the validation set was only 13.5 units of colorimetric intensity away from the training set’s predicted model. This means that even a randomly chosen set of data points can approximate the correlation between the rest of the colorimetric intensity data and naphthalene concentration. While the logarithmic relation between colorimetric intensity and the concentration of naphthalene means that an error of 13.5 in colorimetric intensity will result in higher error at larger concentrations, all calculated values from this residual equation were still the same order of magnitude as the actual naphthalene concentrations they predict. Through future work and continued improvement of the sensor’s data collection, the variance of these data points should decrease, and the improved calibration curve should be able to predict PAH concentration more accurately from colorimetric intensity.

3.3 Discussion

Although the sensor in its current form may be unable to detect PAHs at the EPA limit of 0.8 ppb, it is able to detect down to 10 ppb and provides a satisfactory proof of concept of this novel sensing method with several advantages over traditional methods. The detection limit and sensitivity can be improved using several methods, as described hereafter. In the case of trying to further concentrate the PAH analytes as they move through the Si NF mat, fibers with increased hydrophobicity could be used. While the silica fibers shown are smooth, a different fiber morphology (i.e., beaded) could increase the hydrophobicity of the mat. Beaded fibers increase surface roughness, allowing for air trapped between the fibers and the water droplet to minimize the surface energy and increase the contact angle. This increased hydrophobicity will aid in the prevention of water diffusing out of the scintillation vial through the porous nanofibers. This lack of water in the reaction chemistry would increase the PAH concentration [19, 28–33], allowing for both faster and more apparent color changes in the sensor. Another plausible method to decrease the associated error Would be by creating a box apparatus to inhibit any outside light pollution from reaching the Si NF mat, more consistent pictures can be taken which may lead to a decrease in error bars, as shadows and glare will be eliminated. Each individual Si NF mat has the potential to vary in color and brightness, and to further eliminate variation in color intensity, it may be possible to subtract the color intensity of a picture taken before the reaction occurs from a post-reaction picture to better quantitate the sensor’s ability to detect PAHs.

Naphthalene is a common contaminant in other materials such as soil, cosmetics, and insecticides. In the case of cosmetics, naphthalene is forbidden, but it can be introduced to the environment unintentionally as a byproduct of the synthesis of sodium naphthalene sulfonate.
which is used as a surfactant to manufacture various cosmetics [33]. This naphthalene derivative can contain contaminant concentrations of up to 6% naphthalene by weight, meaning that a gram of sodium naphthalene sulfonate used could contain up to .06 g of naphthalene. This means that potential concentrations of naphthalene as a result of cosmetic run off could be up to 60 ppm [34], which the sensor is more than capable of detecting, provided that the pollution is in a liquid solution stream. The sensor is able to detect naphthalene and PAHs in high concentrations (above 0.01 ppm) in soil and insecticides, which can contaminate groundwater via run-off.

4 Conclusion

An increased color change was successfully observed for higher concentrations of naphthalene in the spiked water samples, as indicated by the higher colorimetric signal for increasing naphthalene concentrations. As expected, a less intense color change is developed for decreasing concentrations of the analyte, as fewer brown quinoid compounds are being formed from the condensation with the formaldehyde and sulfuric acid. The visible colorimetric response images were analyzed, yielding an image intensity. This allowed for a quantification of the visible colorimetric response, permitting either a quick litmus-style qualitative comparison or a more precise quantitative intensity analysis using ImageJ to determine a precise concentration. The proof-of-concept limit of detection (LOD) of the preliminary sensor is 10 ppb of naphthalene, which is less than 2 orders of magnitude from the US EPA limit. It is predicted that through further testing this EPA LOD will be accomplished. While the colorimetric sensor concept presented herein can still be improved upon to reach the EPA LOD and increase accuracy, it is currently the only method of determining the concentration of PAHs that can be performed on-site without a separate preconcentration step. While various detectors and purge and trap methods can be used, the analysis of PAH samples using gas chromatography involves an initial step of extracting the PAHs from the sample, typically requiring harsh solvents and additional laboratory supplies and skills. As a result, this sensor concept has the potential to be well-utilized in agricultural and remote water testing as well as having the capacity to be operated by those without laboratory experience. Table 1 below outlines the advantages of this sensor and its performance relative to other currently used methods. As demonstrated in table 1, the sensor presented herein is fractionally cheaper than current methods, is more easily utilized, and has the advantage of not needing a separate preconcentration step, as purge and trap methods require a Soxhlet extraction or other liquid-liquid extraction method for detection of aqueous PAH pollutants [35]. Future work includes the testing of other PAHs, such as pyrene or anthracene. It is currently unknown whether the sensor can provide a reading for the entire class of polycyclic aromatic hydrocarbons, or whether specific PAHs create varying color intensities at similar concentrations. Further selectivity testing will be conducted using PAHs alternative to naphthalene to determine this. This work will be refined, as improved image detection methods will reduce variance between sensor trials. The sensitivity of the sensor will be improved by using the current setup with an additional layer of hydrophobic polypropylene nanofibers under the silica fibers. This has been shown to increase the sensitivity of colorimetric sensors by more effectively preconcentrating the analytes and not allowing as much water to contact the colorimetric chemistry. Water has been shown to be detrimental to these types of reactions. Transport studies to measure and
improve the collection efficiency of the analytes with relation to mat thickness can be done
to further improve the accuracy of the sensor. Environmental testing with aquatic aromatic
interference will also be done, as this will characterize the robustness of the sensor for field
sampling. Eventually, a portable, self-contained apparatus will be developed to detect and
quantify PAHs at EPA relevant concentrations.
Table 1  A comparison of currently available PAH detection and concentration methods

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* The run time was used ubiquitously for all contaminants/PAHs tested
† Solid sampling
5 Author Declarations

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5.2 Availability of Data and Materials
All data generated or and/or analysed during the current study are available from the
Corresponding author upon reasonable request.

5.3 Authors’ Contributions
Conceptualization: Evan K. Wujcik; Formal Analysis and Investigation: Colton Duprey, Hadi
Rouhi, Saeideh Alipoori, Lauren McLoughlin, Sarah Veres, George Chen, CLint Cook, Olivia
Diaz, Emily Linn, and Yang Lu; Funding Acquisition: Yang Lu, Mark Elliott; and Evan
K. Wujcik; Methodology: Evan K. Wujcik; Supervision: Colton Duprey, Evan K. Wujcik;
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5.5 Conflicts of Interest
The authors declare no conflicts of interest financial or otherwise.

5.6 Ethics Approval
Not applicable

5.7 Consent to participate
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5.8 Consent for publication
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