Portable detection of trace metals in airborne particulates and sediments *via* μ PADs and smartphone

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Particulate matter (PM), a key indicator of air pollution by natural and anthropogenic activities, contributes to a wide spectrum of diseases that lead to a shortening of life expectancy. It has been recognized that trace metals in airborne PM are highly toxic and can be correlated with lesion in respiratory, gastrointestinal, immunological, and hematological systems. Traditional methods for trace metal assay require sophisticated instrumentations and highly trained operators in centralized laboratories. In this work, by integrating the technologies of microfluidic paper-based analytical devices, additive manufacturing, smartphone, and colorimetric sensing, we developed the first smartphone based paper microfluidic platform for portable, disposable, and quantitative measurements of cobalt (Co), copper (Cu), and iron (Fe) in ambient air and street sediments. On a single A4-sized paper, 48 devices were fabricated in under 30 s with a total cost of $\sim \$1.9$. On each device, 12 reaction units were patterned and used for colorimetric tests. Particulate samples from urban ambient air and street sediments were collected, processed, and analyzed. Signals of the on-chip complexation product were recorded using a smartphone camera and processed by a self-developed app on an iOS system. For precisely controlling the object distance, chip position, and luminance, a hand-held 3D cellphone housing was designed and printed. The detection limits of Co, Cu, and Fe were determined to be 8.2, 45.8, and 186.0 ng, while the linear dynamic ranges were calculated to be 8.2–81.6, 45.8– 4.58×10^2 , and 1.86×10^2 – 1.86×10^3 ng, representing a practically relevant device performance with a significant reduction in the detection cost and time consumption. Trace metals in ambient air and sediments of two cities in China have been quantified portably, thus demonstrating the utility of our system in improving strategies for air pollution control in low-resource settings. Published by AIP Publishing. <https://doi.org/10.1063/1.5003308>

I. INTRODUCTION

PM, standing for particulate matter (or particle pollution), is a mixture of solid particles and liquid droplets found in the air.¹ Studies have shown that the exposure to particulate matter can be linked to various human diseases including, but not limited to, hematopoietic,² neural,³ hepatic⁴ cardiovascular,⁵ and pulmonary⁶ abnormalities, immune disorders,⁷ and premature defects,⁸ as exposing to PM contributes to the increasing morbidity and mortality of these diseases.^{9–11} It is estimated that around 2.1 million deaths are caused by PM each year.¹² The components of PM can generally be classified as carbonaceous fractions and inorganic components consisting of crustal elements, trace metals, and ionic species.^{13,14} Of these, a confirmed PM component exerting toxic effects on human being is trace metals.¹⁵ Epidemiological studies

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have demonstrated that exposure to trace metals can impair human health at concentrations commonly found in urban areas.^{9,16,17} Conventionally, PM in the ambient air is collected by professionals in meteorological stations and delivered to offsite chemical laboratories for further analysis. Typical instruments used for analysis include Atomic Absorption Spectroscopy, Inductively Coupled Plasma Optical Emission Spectroscopy, and Mass Spectrometry. Although they can provide precise and sensitive PM information,^{18–20} these sophisticated instruments are complex and require highly trained personnel to operate. In addition, the variation in spatial and temporal air pollution is an important environmental indicator, and obtaining such information often requires real-time monitoring of the current measurement condition and efficient (or even onsite) data analysis. These requirements are yet to be met by the conventional measurement approach, and therefore, novel methods for portable quantifying trace metals in airborne PM are still needed.²¹

Microfluidic paper-based analytical devices (or μ PADs) are a promising technology for developing simple, cost-effective, portable, and disposable platforms for biochemical assays.^{22–24} Compared to traditional materials (e.g., polydimethylsiloxane, polymethyl methacrylate, or parylene), the merits of paper include (1) low-cost and ubiquitousness, (2) high biocompatibility, (3) power-free for liquid transportation, (4) environmental friendliness, and (5) scalability (i.e., printing and roll-to-roll manufacturing friendly).^{24–26} Environmental hazards in contaminated soil,^{27,28} waste water,^{29,30} and ambient air^{31,32} have been studied by μ PADs. Particularly, trace metals in industrial ash or real air have been measured *via* a series of well-designed paper chips and detailed protocols have been developed by Henry Group.^{33–36} In parallel, for further reducing the complexity in μ PAD-based biochemical analysis, the smartphone and paper chips have been combined.^{37–39} The hybrid of smartphone and microfluidic devices simplifies mobile sensing (termed as MS²) and provides an unprecedented solution for the new generation of instrument-free scientific applications.⁴⁰ For measuring the trace metals using MS,² colorimetric methods are suitable. In MS² based colorimetric sensing, specialized imaging instruments such as digital color detectors, photodetectors, spectrophotometers, and charge-coupled devices (CCDs) in traditional methods can be omitted. Signals of trace metal complexation testing can be portably captured and stored merely by a phone's camera, and the data interpretation can be finished in a custom-tailored app. Most recently, the main application of MS² is global disease diagnosis,²⁴ and there is still a need for developing a MS² system for airborne trace metal detection.

In this work, we fill the void by developing the first smartphone based paper microfluidic platform for portable, disposable, and quantitative characterization of multiple airborne trace metals. Integrating the technologies of μ PADs, additive manufacturing, smartphone, and colorimetric sensing, the assembled system is mounted on an unmanned aerial vehicle (UAV) and a sampler is also used for collecting PM in ambient air so that the sampling conditions and locations can be precisely recorded for better air pollution data analysis. The μ PADs are fabricated batch-to-batch, using a custom designed simple photolithographical process. A total of 48 chips that are capable of performing 576 PM tests can be patterned on an A4-sized (210 × 297 mm) filter paper within 30 s with a total cost of \$1.92, well suited for disposable use. Also, by using a self-built iOS app, the concentration of trace metals can be easily quantified via cell phone photography and automatic colorimetric image grayscale conversion. During each image capture, the μ PADs' position and distance to the camera lens and illumination dosage are controlled by a 3D printed cell phone housing (the chip bin). The portable system is calibrated by standard solutions of Co, Cu, and Fe, and the limit of detection (LOD) values of 8.2, 45.8, and 186.0 ng of three metal assays are found to be practically useful, respectively. Finally, PM samples of ambient air and street sediments in Fuzhou City (China) are studied, thus demonstrating the utility of our system for portable, disposable, and cost-efficient trace metal analysis in airborne PM.

II. PROCEDURE AND DEVICE

A. Operating procedure

For collecting PM at different altitudes, a foldable quadcopter drone (DJI Mavic Pro, DJI-Innovations Co., Ltd., Shenzhen, China) with a self-assembled sampler was employed. The

compact size ($83 \times 83 \times 198$ mm) and the low weight (~ 0.74 kg) of the UAV allowed easy handling and transportation of the system between sample collection sites, and the stability of the drone during flight provided a secure platform for the sampler. A commercial PTFE (polytetrafluoroethylene) filter membrane with a mean pore size of $\sim 2.0 \mu\text{m}$ was selected for PM sampling. In parallel, sediments at the street level were collected using a clean sample bag directly. The collected PM was then dissolved in acid followed by neutralizing treatment for subsequent on-chip colorimetric assay. For the metals Co, Cu, and Fe, standard chrysoidine-G, dithiooxamide, and 1,10-phenanthroline monohydrate were selected as colorimetric ligands, respectively. The complexation principles of metals with the ligands are illustrated in the first section of the [supplementary material](#).

The locations of on chip reaction zones were obtained by the self-developed iOS app using an intact chip. After coding the information of the zones into the Swift program, an array of μPADs was fed into the chip bin for consecutive chip-to-chip image photographing by an iPhone's rear camera. The app converted colorimetric images from the 32-bit RGBA format to the 8-bit grayscale for quantitative analysis. Additionally, since we used a white intact paper as the reference, we inverted the grayscale images so that intensity measurements would yield a positive slope when plotted versus trace metal concentrations. Finally, the mean colorimetric values of the reaction zones and the corresponding trace metal concentrations were presented on the user's interface in formats of tables and bar charts. A schematic of the whole operating procedure is shown in Fig. 1(a).

B. μPAD design

A μPAD consists of one sample inlet ($\Phi = 7.0$ mm), 12 detection reservoirs (DR, $\Phi = 3.0$ mm), and hydrophilic channels connecting them [Fig. 1(b)]. In addition, 12 reference reservoirs are also included outside the DRs for intra-assay negative control (INC, $\Phi = 3.0$ mm). The dimension of a μPAD is measured to be $30.0 \times 30.0 \text{ mm}^2$ with a detection area of $25.0 \times 25.0 \text{ mm}^2$. Therefore, a single A4-sized paper (210.0×297.0 mm) can allow a maximum of 48 μPAD to be printed per batch. The photomask used for feature patterning is made using a film output printer (customer-modified Epson 1430 printer) with a droplet size of 1.5 pl and a resolution of 5760×1440 dpi. The bottom side of the μPADs is covered with a layer of clear packing tape to prevent solution from leaking out the paper during testing.

C. μPAD fabrication

μPADs were fabricated batch-to-batch using the photocrosslinking technique. The photore-sist used in photocrosslinking included stearyl acrylate (monomer for UV polymerization),

FIG. 1. (a) Schematic of the portable detection of trace metals in airborne PM and Sediments; (b) design of the μPAD using CorelDRAW software; (c) schematic of the chip fabrication process; (d) 48 (8×6) chips on a single A4-sized filter paper and the details of an individual chip (upper).

2,2-dimethoxy-2-phenylacetophenone (photoinitiator for initializing radical polymerization), and 1,10-Bis(acryloyloxy)decane (solvent and crosslinker for the cured co-polymer). The mixture of the photoresist precursor was stored in an incubator at a temperature of 65 °C. More details could be found in Fig. 4 of the [supplementary material](#). Rectangle-shaped (460 × 570 mm) Whatman[®] qualitative filter papers of grade 1–4 were cut into A4 paper size sheets. The filter papers were next submerged in a photoresist mixture filled glass tank (300 × 300 × 50 mm) for photoresist coating. Two sheets of regular A4 papers were then used to clamp the coated filter paper to absorb the excess photoresist. Next, the filter paper was transferred to a UV curing machine (with an exposure density of 250 mJ/cm²) for 3.0 s at a wavelength of 365 nm. The UV light was homogenized by passing through two layers of plastic diffusers prior to reaching the film mask. Finally, the exposed paper was instantly developed by immersing in acetone solution for 5.0 s to solidify the on-paper hydrophobic architectures. The entire fabrication could produce up to 48 ready-to-use μ PADs, which had a total cost of \$1.92 and were completed in under 30 s. The fabrication process flow is illustrated in Fig. 1(c), and the detailed fabrication cost assessment is presented in Table I of the [supplementary material](#).

III. EXPERIMENTS

A. Materials

Materials and reagents were used as received from manufacturers. Octadecyl acrylate, 2,2-dimethoxy-2-phenylacetophenone, and 1,10-decanediol diacrylate were purchased from Tokyo Chemical Industry (Tokyo, Japan). Whatman qualitative filter paper in large rectangular shape, Grade 1 to 4, and PTFE membrane filters were purchased from GE Healthcare Life Sciences (Pittsburgh, PA., USA). Iron chloride hexahydrate, 1,10-phenanthroline, poly(acrylic acid), acetic acid, sodium acetate anhydrous, Copper sulfate pentahydrate, dithiooxamide, sodium chloride, Cobalt chloride, chrysoidine, polyethylene glycol, and sodium hydroxide were purchased from Aladdin Bio-Chem Technology (Shanghai, China). Hydrogen chloride, methanol, and isopropanol (IPA) were purchased from Xilong Scientific (Shantou, Guangdong, China). Hydroxylamine was purchased from Sinopharm Chemical Reagent (Shanghai, China). Containers were rinsed with deionization (DI) water prior to use. More material information is listed in Table II of the [supplementary material](#).

B. Hardware

A carbon fiber reinforced filament (CFPLA, 80SCarbon-2, 80s Studio, Shenzhen, China) was used for building the chip bin. Compared to common PLA filaments, this material provided better structural integrity and surface roughness and had a lower density. Components of the chip bin were designed using PTC Creo 3.0 and manufactured using a 3D printer (Finder[®], FlashForge Inc., Zhejiang, China). The chip-bin consisted of 3 components: a cover (with two inner slide rails), a front board (with two slide rails), and a main body (with four outer grooves, two inner cavities, a pair of chip entrance and exit) as shown in Fig. 2(a). On the inner wall of the main body, an adhesive ruler tape was affixed on the wall for measuring and fixing the object distance [Fig. 2(b)]. During operation, the A4-sized paper with 48 chips was cut into ribbon-shaped arrays for consecutive chip-to-chip colorimetric analysis as shown in Figs. 2(c) and 2(d). More details of chip bin design can be found in Fig. 5 of the [supplementary material](#).

Graphene-enhanced polylactic acid (GPLA-5K, PMG 3D Tech., Shanghai, China) was used for constructing the PM sampler. The sampler's frame structure was designed using software PTC Creo 3.0 ([supplementary material](#), Fig. 6). The same 3D printer was used to build the object. After slicing using the FlashPrint software, the frame was built layer by layer at an extruder temperature of 215 °C. The PM_{2.5} sampler can be reversibly mounted on a flying UAV as shown in Figs. 2(e)–2(g). Specifically, a turbofan (San Ace 40, Sanyo Denki, Osaka, Japan), a PTFE filter film with a pair of clips, a lithium battery (8000 mA), and a wireless remote control switch were included in the sampler. The total mass of the sampler is 0.18 kg, and the battery can support the turbofan for operating more than 5.5 h per single charge. The air flow rate

FIG. 2. Experimental set-up. (a)–(d) Smartphone and 3-D printed modules of the hand-held experimental platform; (e) and (f) UAV with the PM sampler; (g) UAV and sampler in test; (h) Gray intensity readouts of DRs; (i) Bar charts of gray intensities of DRs and INCs; (j) Metal amount readouts; (k) Bar charts of metal amounts in DRs and INCs (for estimating sample contamination).

through the sampler could be adjusted by the input voltage, and we used a flow rate of 4 l/min for the PM collection. After sampling, the drone with the PM sampler returned and the PTFE film was unloaded from the sampler for subsequent assays.

C. Mobile app

Based on the toolset of Xcode 8.0 and Swift 3.0 programming language, a mobile app on the iOS system was developed for converting RGB images to the grayscale, detecting circular shaped patterns, and calculating the gray intensity. Values of R, G, and B channels for each pixel were extracted and converted into the grayscale using the luminosity method. Since the diameter of each on-chip DR and INC was 3.0 mm, accounting for approximately 38 pixels in a 2448×3264 image (a typical image size obtained using an iPhone 5s rear camera), we set the pixel range to 37–39 for colorimetric detection. To increase the calculating efficiency, the detection area was limited to the middle section of an image (2448×1000). Finally, mean gray values of DRs were calculated and presented on user's interface of the app [Fig. 2(h)]. For the study of multiple samples, the mean intensity values of 6 pairs of DRs were obtained to allow parallelized tests of 3 different metals. Bar graphs describing gray intensities were plotted on the following window of the app [Fig. 2(i)]. Furthermore, the intensity values can be correlated with trace metal concentrations after calibration tests [Figs. 2(j) and 2(k)]. Generally, a typical image captured by iPhone 5s' rear camera can be processed within 3.5 min.

IV. RESULTS AND DISCUSSION

A. Characterization of the microfluidic pattern

We first compared the intact and patterned papers of different types ranging from Whatman grades 1 to 4 using optical microscopy and measured the contact angles of these patterned papers. For all papers, with identical luminance from the same light source, the images of patterned papers were brighter than the intact ones [Fig. 3(a)]. Of these, grade 3 paper had the highest brightness. Since the cross-linked polymers were more likely to be retained by the cellulose to enhance the optical reflectance of the filter papers, a brighter image represented more absorbed molecules. Also, at room temperature and under standard atmospheric pressure,

FIG. 3. (a) Micrographs of intact and patterned filter papers of different types (objective magnification: 10 $\times$); (b) Contact angles (CAs) on the droplet-hydrophobic pattern interface; (c) Intact chip for circle detection; (d) Colorimetric image processing; (e) Raw digital map of on-chip Fe colorimetric assay; (f) Digital map of a chip for inter-assay negative control; (g) Digital map of on-chip Fe colorimetric assay after background noise subtraction.

the contact angles on the papers' hydrophobic surface were measured using a profilometer (PT-705A, Precise Test Inc., Guangdong, China). As shown in Fig. 3(b), contact angles on 4 different patterned papers were determined to be beyond 90°, indicating hydrophobic surfaces. Meanwhile, the contact angle of the grade 3 paper ($\sim 122.5^\circ$) was greater than the other ones due to particle retention and paper thickness. Particle retention is an attribute in paper making processes, indicating that filler and/or other fine particles are retained in the finished paper and thickness can affect liquid ink penetration and absorption. Based on information from the manufacture, grade 3 paper has the smallest particle retention (6 μm) and longest diffusion length (390 μm), which can retain more molecules in a given time. Therefore, Whatman grade 3 paper was chosen for the following work.

B. Validation of on-chip colorimetric assay

It had been reported that levels of aerosolized Fe were higher compared with other metal constituents in PM. Therefore, we used Fe to demonstrate the validity of our portable testing system. A fabricated μPAD was inserted and fixed in the chip bin so that the cell phone camera was aligned with the center DRs and INCs [Fig. 3(c)]. Next, after on-chip reagent preparation (detailed in [supplementary material 4](#)), 10.0 mg of $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ was dissolved and homogenized in 1.0 ml of DI water to obtain Fe at a concentration of $\sim 2.1 \mu\text{g}/\mu\text{l}$. 1.8 μl of the Fe solution was then pipetted onto the μPAD inlet area, and 1.0 μl of DI water was subsequently pipetted onto the inlet as well to fully drive the Fe solution to the 12 DRs. After completely drying, the μPAD was ready for digital colorimetric analysis [Fig. 3(d)]. Using the iOS app, intensity values of each DRs and INCs were obtained and plotted [Fig. 3(e)]. For negative control, a μPAD from the same batch was also placed in the chip bin and colorimetric ligands and buffer solutions without Fe were used [Fig. 3(f)]. Finally, the gray value of the negative control was subtracted from the sample solution value to obtain absolute intensities of Fe assay [Fig. 3(g)]. We also compared the App obtained Fe greyscale intensity values with ImageJ (NIH, MD, USA), a commonly used image processing tool. As a result, the difference in mean and maximum and minimum intensity values obtained using App and ImageJ was below 3.3, which is negligible compared to the absolute Fe intensity value. In addition, although the background noise signals were relatively high due to the white-color paper background, the intensity signal-to-noise ratios of the on-chip DRs and INCs were still sufficient for quantitative characterization of Fe

in solution [Fig. 3(g)]. These results verified the utility of the portable system in quantifying the trace metal concentration in solution.

C. Calibration tests

Next, we used a series of experiments to correlate trace metal concentrations with detected grayscale intensities and define the limit-of-detection (LOD) of our portable system. To do so, colorimetric assays of three metal solutions with 10 concentrations were performed. 0.1 mg of CoCl_2 and 1.0 mg of $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ and $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ were dissolved in 1.0 ml of DI water. All solutions were diluted into concentration ranging from 0.1 to 1.0 mg/ml, corresponding to metal concentration ranges of 4.54–45.4 $\mu\text{g/ml}$, 0.03–0.25, and 0.02–0.21 mg/ml, respectively. Next, 1.8 μl of each metal solution with 1.0 μl of DI water was pipetted onto the μPAD inlet consecutively. For a single on-chip DR, 0.15 μl of metal sample solution was introduced on average. The resulting metal reaction with the colorimetric ligands at different metal concentrations is shown in Figs. 4(a)–4(c). Intensities of each DR were obtained using the app (not shown here). To minimize the bias caused by the flow resistance variation in channels, the maximum and minimum intensity values of 12 readouts were excluded. After subtracting the background noise, mean intensities of each DR were plotted versus the mass of the trace metals in solution. For individual chips (including 12 DRs), the linear dynamic range (LDR) over which the grayscale intensity was directly proportional to the metal mass in solution was determined to be 8.2–81.6, 45.8–458.4, and 186.0–1860.0 ng for Co, Cu, and Fe, respectively. The LOD of the portable system for the tested 3 metals was also characterized to be 8.16, 45.84, and 186.00 ng, respectively. Generally, parameters of LDR and LOD were defined by many factors including μPAD design, fabrication, and sensing principle. The calibration tests for all metals were repeated at least 6 times, and the standard deviations of these tests were obtained to be 1.21, 2.99, and 1.1 [indicated as error bars in Fig. 4(d)], respectively. The calibration testing results of each DR were stored in the app program and used for multiple metal colorimetric assays by smartphone. Furthermore, the effect of built-in cameras of different iPhones on metal quantification readouts was verified to be negligible. This information is included in [supplementary material 5](#).

D. Detection of trace metals in airborne PM and sediments

Once the μPADs have been successfully calibrated, the portable system was used to evaluate trace metals in airborne PM metal. We selected urban spots in cities of Shanghai and

FIG. 4. Calibration testing. Colorimetric assay of Co (a), Cu (b), and Fe (c) with gradient concentrations. The label on the axis means the dilution times; (d) Calibration curves of the three metals. Standard deviations were obtained by 6 repeated assays.

[Fig. 5(a)] Fuzhou [Fig. 5(b)] in China and collected PM using the UAV samplers. The UAV with the sampler was controlled to fly and land on rooftop of pavilions at Shanghai Yat-sen Park ($\sim$ N31.22, E121.42) and 5-level buildings in Fuzhou University Town ($\sim$ N26.05, E119.21). Also, street level PM sediments at the corresponding locations were collected manually. After collecting, the PTFE membrane was removed from the sampler and 20 μ l of concentrated nitric acid was pipetted onto the membrane followed by adding 100 μ l of DI water for dilution. Next, 32 μ l of sodium bicarbonate (0.5 M) was added to neutralize the acid on the membrane, which was then transferred to a 50 ml Erlenmeyer flask containing 10.0 ml of DI water for a 0.5-h ultrasonic treatment. Finally, the membrane was removed from the flask, and the DI water was evaporated to obtain modulated metal solution for downstream assay.

Amounts of Co, Cu, and Fe in airborne PM at selected locations were measured and are shown in Figs. 5(c) and 5(d). For quantifying trace metals in airborne PM in Shanghai, mean values of the three metals were characterized to be 0.0, 135.4, and 197.21 ng (equivalent to 0.0, 141.04, and 205.43 ng/m³). Meanwhile, the tests revealed that the metal components in air PM in Fuzhou were 0.0, 75.42, and 195.73 ng (equivalent to 0.0, 78.56, and 203.89 ng/m³). The value of zero means that the metal concentration in air PM was below the LOD of this portable measurement approach. Nevertheless, the LOD of this portable system is still much lower than the recommended metal concentration in air PM, making the portable system well-suited for monitoring air pollution. Similarly, for sediments in Shanghai and Fuzhou, mean values of the metal concentrations were 44.33, 228.40, and 590.46 ng (or 18.2, 228.52, and 378.39 ng/m³) as shown in Fig. 5(e). It can be concluded that Fe has the highest concentration out of the three tested metals in both air PM and sediments in the two cities, which is expected. In addition, the metal concentrations are in general higher in sediments than the higher altitude airborne PM samples, which is also expected. Compared to Shanghai, the trace metal concentrations are lower in Fuzhou, indicating better air quality. Also, it is noted that the sediment sample from location 5 in Fuzhou showed a significantly elevated metal concentration level compared to other locations. This can be explained by the nearby construction of a subway station releasing more trace metals in air and soil. Although the selected spots in Shanghai and Fuzhou were not heavily polluted, the presented approach and system demonstrated the ability of quantifying low-abundance metal in airborne PM_{2.5}, which can be used for more spatial and temporal atmospheric pollution detection.

V. CONCLUSIONS

This paper presented a portable, integrated system for analyzing low-abundance metals in the airborne PM and sediments by incorporating paper-based microfluidics, smartphone

FIG. 5. Metal component assay of airborne PM and street sediments. PM sampling locations in Shanghai Yat-sen Park (a) and Fuzhou University Town (b); (c) Amounts of Co, Cu, and Fe in airborne PM of Loc. 1#–4# (unit: ng); (d) Amounts of Co, Cu, and Fe in airborne PM of Loc. 5#–8# (unit: ng); (e) Amounts of Co, Cu, and Fe in sediments of Loc. 1#–4# (left) and 5#–8#.

colorimetric detection, 3D rapid prototyping, and unmanned aerial vehicles. Co, Cu, and Fe in both airborne PM and sediments were collected and quantitatively characterized using the system with significantly reduced analysis time and cost. The detection limits of the system for the selected three metals were found to be 8.2, 45.8, and 186.0 ng, while the linear dynamic ranges were calculated to be 8.2–81.6, 45.8– 4.58×10^2 , and 1.86×10^2 – 1.86×10^3 ng, well-suited for monitoring low-abundance metals in airborne PM. The real pollutants in ambient air and sediments of Shanghai and Fuzhou City in China were collected and analyzed. This demonstrated the system's utility in quantitatively characterising metal concentrations in airborne PM at practically useful sensitivity with significantly reduced cost, time consumption, and acquirement for equipment training. This portable and low-cost tool also holds great potential in enabling customized air PM analysis in low-resource settings and provides quantitative information in unsafe environments.

SUPPLEMENTARY MATERIAL

See [supplementary material](#) for further information of colorimetric assay principle, chip fabrication, 3-D chip bin design, materials, on-chip operation, and smartphone's camera tests.

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