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HazeL: A Low-Cost Learning Platform for Aerosol Measurements

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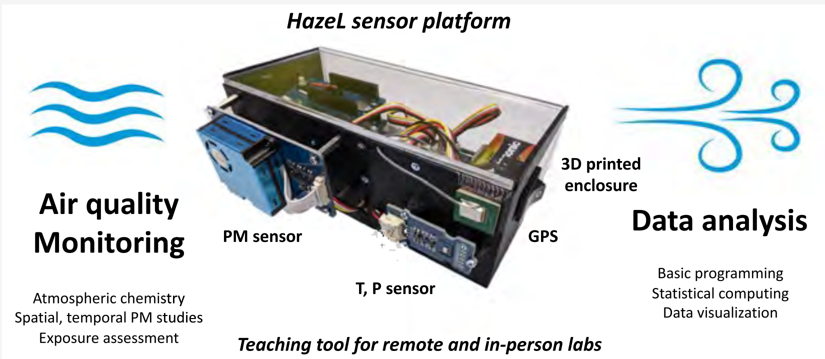

ABSTRACT: The switch to online instruction during the COVID-19 pandemic forced educators to adapt hands-on environmental engineering experiments to a remote curriculum previously conducted in a laboratory using expensive analytical instruments (> $2000 per device). Here, we describe how we developed a low-cost (<$200) aerosol sensor platform as a successful solution for supporting remote laboratories on air quality for environmental engineering courses in Spring 2021, and continued for in-person classes in Spring 2022. This sensor platform, called HazeL (Haze Laser Sensor), consists of an externally mounted aerosol sensor, a GPS receiver, and temperature and pressure sensors coupled to an Arduino MKR WiFi 1010 microcontroller connected via a Grove system. Using a project-based learning approach and implementing the scientific method, students worked asynchronously to design experiments, collect aerosol measurements, and analyze and visualize data using the R programming language. Students generated hypotheses regarding factors affecting air pollution, measured $\geq$0.3 μm particles in different locations, tested differences between samples, and rejected the null hypothesis if appropriate. HazeL was also used for projects on data processing and statistical inference in an upper-level computational course. We present an instructional guide on manufacturing the HazeL platform and using it as a teaching tool for enhancing student experiential learning, participation, and engagement.

KEYWORDS: *Atmospheric Chemistry, Environmental Chemistry, Distance Learning, Hands-on Learning, Instrumental Methods, Laboratory Equipment/Apparatus, First-Year Undergraduate/General, Upper-Division Undergraduate*

■ BACKGROUND

The COVID-19 pandemic upended the education system,[1,2] leading numerous institutions to adapt previously synchronous in-person courses to remote instruction. Adapting environmental science and engineering laboratory courses for remote instruction poses many challenges. These courses often require hands-on engagement with laboratory instrumentation for a quality active-learning experience.[3,4] For example, prior to the pandemic, most environmental engineering courses included hands-on activities for students to investigate different environmental systems, chemical phenomena, properties and reactions, using a variety of laboratory apparatus and instruments.[5] Shifting these laboratory-intensive courses to remote instruction was difficult, since instruments cannot be shipped to students across different locations due to safety and resource constraints. While some course activities can be transitioned to web-based and computer-simulated activities, these tools cannot be considered equivalent replacements for hands-on laboratory experiences.[5] Innovative tools in environmental engineering are needed to ensure students experience

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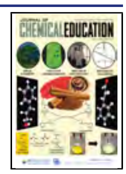

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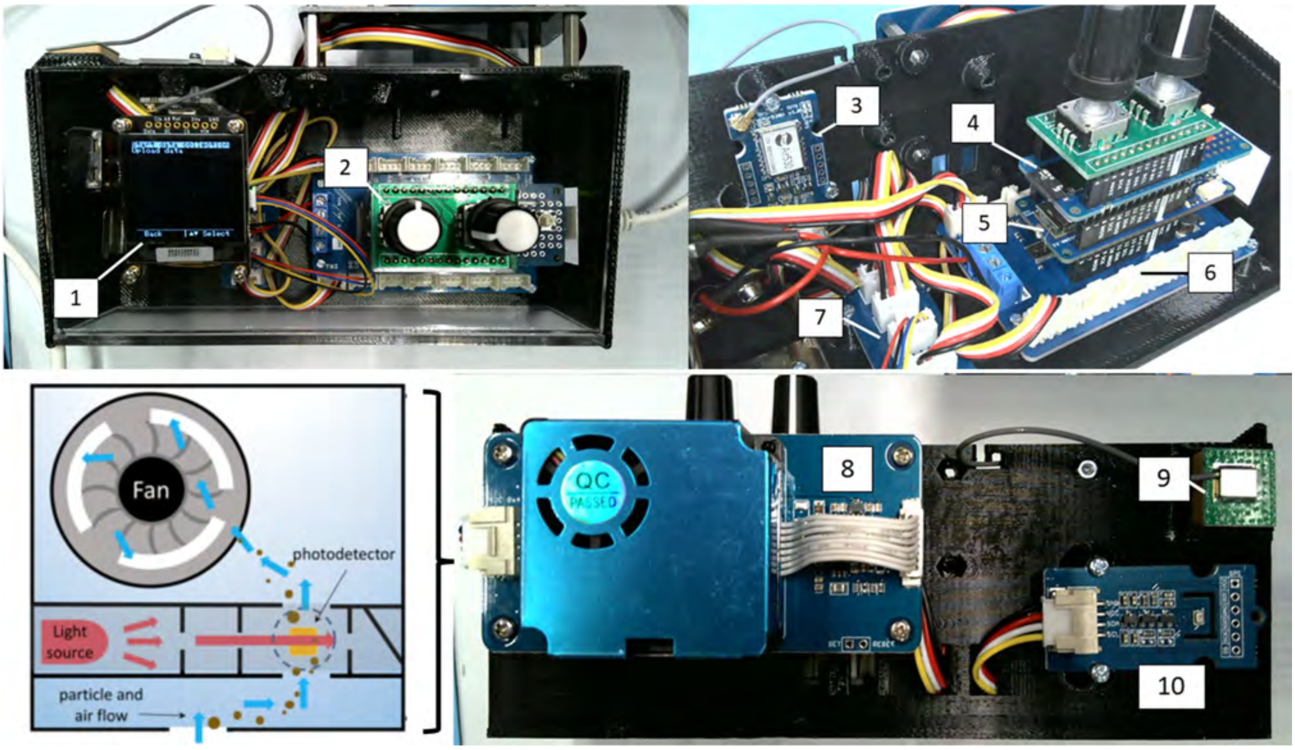

Figure 1. Components of the HazeL sensor platform. (1) OLED display, (2) Rotary encoders mounted on custom printed circuit board, (3) GPS module, (4) MKR SD shield with microSD card, (5) Arduino MKR WiFi 1010, (6) MKR connector carrier, (7) Grove I2C hub, (8) HM3301 particle counter, (9) GPS antenna, (10) Temperature and pressure sensor. Air is sampled using a fan and travels through the laser path and detection area (dashed circle line). Scattered light is used to estimate particle concentration. Details about each component are available on GitHub (https://github.com/brownby/HazeL) and are also provided in the Supporting Information.

hands-on procedures with the same academic rigor as they would in a laboratory setting.

Air quality is a core topic in the environmental science and engineering curriculum at Harvard College, where students study air pollution, indoor/outdoor aerosols, chemical processes in the atmosphere, and their health and ecosystem effects. Previously, our laboratory on air quality was taught using a limited number of commercial research-grade particulate matter (PM) counters (>$2000 each). Using these particle counters during the transition to a remote laboratory was no longer feasible due to limited resources, so we looked for an alternative solution. In recent years, a growing number of manufacturers have produced compact, cheap (i.e., ∼100× less expensive than commercial PM monitoring equipment), and portable sensors (e.g., Plantower, Honeywell, Seeed, Amphenol), which are made mainly for industrial applications such as in air purifiers, air conditioners, ventilation systems, vehicle air cleaners, and smart home equipment.[6,7] However, these sensors are not readily designed for teaching purposes and require integration into a complete functional platform (e.g., enclosed for field use, connected to a microcontroller, sensing and communication modules, among others). Recent technology reports published in this journal addressed this gap using the Arduino platform.[8−11] For example, the ChemDuino[8] and the ROXI[9] systems utilized the capabilities of Arduino to teach concepts like temperature and pH. For air quality, sensor devices for measuring carbon dioxide[12] and secondary organic aerosols (AIRduino)[13] have also been developed. If more teaching tools like these are available, it can allow instructors to create more engaging activities that can be adapted for their courses. However, the current literature on low-cost educational sensors, particularly particle counters, remains scarce and there are limited open-sourced tools available to help instructors build and implement such devices.

In this paper, we present a cost-effective sensor platform for aerosol measurements, named HazeL (Haze laser sensor), that can be easily manufactured for both in-person and remote education settings. In addition to the particle counter, HazeL included other components such as GPS, temperature and pressure sensors, an OLED screen, a 3D-printed enclosure for protection, as well as specific data reporting and uploading schemes for subsequent analysis in R.[14] For remote instruction in Spring 2021, HazeL was shipped to over 40 students worldwide and was used to study spatial and temporal variability of aerosols in indoor and outdoor environments. This activity was adapted for in-person experimentation in Spring 2022, and over 60 HazeLs were provided to students on campus. Here, we provide technical information for building and operating HazeL (e.g., source files, construction drawings, schematics, codes), and discuss how it was applied as a hands-on experimental activity to study air quality.

■ MATERIALS AND METHODS

Experimental Overview

The HazeL platform was used in a Spring 2021 and 2022 undergraduate "Introductory Environmental Science and Engineering" course (ESE 6) in a laboratory on air chemistry and pollution. ESE 6 is a foundational course in the environmental engineering curriculum, where students learn fundamental concepts in environmental systems, biogeochemical cycles, effects of human activity to these natural cycles, and engineering solutions to complex environmental issues. The course also introduces students to data analysis using the R programming language.

HazeL was also used in Spring 2021 and 2022 for an upper-level undergraduate course, "Data Analysis and Statistical Inference in the Earth and Environmental Sciences" (EPS/ESE 102). EPS/ESE 102 is a practice and application-oriented course covering statistical inference, hypothesis testing, regressions, Monte Carlo methods, analysis of variance, time series analysis, and data filtering and visualization. The remote and in-person version of the course used HazeL for its hands-on learning component, using real data drawn from atmospheric and geophysical observations.

For these two courses, HazeL was used for the following: (1) to design experiments for measuring aerosols (>0.3 μm particle size) in indoor and/or outdoor environments, and (2) to analyze and visualize data using R. For measuring aerosols, students were instructed to observe the variability of aerosol differences between two different locations of their choice, looking for influences of traffic or other sources of aerosols. They were also instructed to measure variability in airborne particulate matter concentrations over time in a single location and assess their levels of exposure to aerosols at home. For data analysis, students learned hypothesis testing, data preprocessing and cleaning (editing, trapping bad data), time stamps and synchronization, and low-pass and high-pass filtering. They also estimated the trends and random components (variances) at different time scales, and used these to make statistical inferences about sources of aerosols, and the exposures they or other people receive. For in-person experiments, an additional calibration step was included using laboratory-grade particle sensors (see Supporting Information S1, Text S2 for details).

Components of the HazeL Platform

Design files, including system diagrams, 3D printing files, and codes are described below and are available on GitHub (https://github.com/brownby/HazeL) and in the Supporting Information. A list of parts used for the device, including pricing, is shown in Supporting Information S1, Table S1.

The aerosol and dust sensor within HazeL measures size-resolved PM concentrations in ambient air. The sensor uses standardized size distributions and particle densities to report results as atmospheric PM 1.0, PM 2.5, and PM 10, and as cumulative counts of particles by maximum diameter (>0.3, >0.5, >1.0, >2.5, >5.0, and >10.0 μm pcs/0.1 L).

The sensor consists of a Shenzhen Co., Ltd. HM3301 Dust Sensor (Figure 1), which is comparable to other commercial sensors of very similar design commonly used for industrial applications.[6,15] The sensor is a simple, compact laser scattering device that requires low voltage and low power for battery-operated portable air quality monitoring. It is equipped with a small fan to provide controlled air flow to transport the particles into the laser path. Particles in the detection area produce pulses of scattered light, with a count rate proportional to the particle concentration and pulse intensity related to particle size. The scattered light is detected by the photodetector (90° angle from the laser diode) and then processed by the signal conditioning circuit. The sensor has a built-in system to convert and process the photodetector signal into digital data.

To complement particle count data, HazeL also contains a GPS receiver and temperature and pressure sensors (BMP280) coupled to an Arduino MKR WiFi 1010 microcontroller. Additionally, HazeL is equipped with an Internet-of-Things (IoT) capability and is also programmed for remote access and analysis of data through ThingSpeak.[16] While the IoT capabilities were not used in the first iteration of the courses, the hardware used supports and is programmed to allow uploading the collected data to ThingSpeak for future activities. HazeL was designed to be fully functional even when not using the IoT capabilities. Thus, the collected particle data are displayed on an OLED screen in real-time and are simultaneously saved onto a microSD card for postprocessing, along with important metadata such as the temperature, pressure, GPS coordinates, and UTC timestamp. HazeL employs the Grove connector system, a modular toolset developed by Seeed Studios[17] to wire all components in the device. This plug-and-play platform enabled us to manufacture 60 devices in 2 weeks.

3D-Printed Enclosure

The enclosure for the device was designed with a minimal volume (15.9 cm × 6.5 cm × 8.5 cm), while maintaining ease of manufacturability and assembly (Figure S1). An enclosure with four walls was designed to be quickly (6 h/device) and inexpensively 3D printed ($5/piece) on any FDM 3D printer using 69 cm^3 of acrylonitrile butadiene styrene (ABS) polymer. The front and top of the enclosure were left open to allow a technician to assemble the device easily. Since the device needed to be weather-resistant and resilient, a removable top and front panel were also designed. These panels were laser cut from clear acrylic to allow students to understand the electronics involved in the system.

Electronics

A simplified electrical schematic of HazeL is shown in Figure S2. The connections to the GPS module, dust sensor, temperature and pressure sensor, and OLED display are via Grove connectors on the MKR connector carrier. The connector carrier not only holds the Arduino and provides convenient access to Grove connectors; it also has a built-in level shifting circuitry to shift the 5 V logic of the Grove modules to the 3.3 V logic of the MKR WiFi 1010. The MKR SD proto shield, mounted on top of the MKR1010, has a microSD card holder, as well as rotary encoders mounted on custom printed circuit board used to interact with HazeL (e.g., setting initial timestamp, viewing collected data files, among others).

The HM3301, BMP280, and OLED display all communicate with the Arduino MKR1010 via the common interintegrated circuit (I2C) communication protocol. The GPS module communicates using the universal asynchronous receiver-transmitter (UART) protocol, and the SD card uses the serial peripheral interface (SPI) protocol. The code for communicating with these various modules uses various libraries, of which 2 were custom written and 2 were open source (see https://github.com/brownby/HazeL for more details). Any custom written libraries are now open sourced along with the rest of the code for HazeL. Regardless of the library, the underlying hardware communication uses the built-in Arduino libraries Wire (for I2C), Serial (for UART), and SPI, and thus should be compatible with most Arduino microcontrollers.

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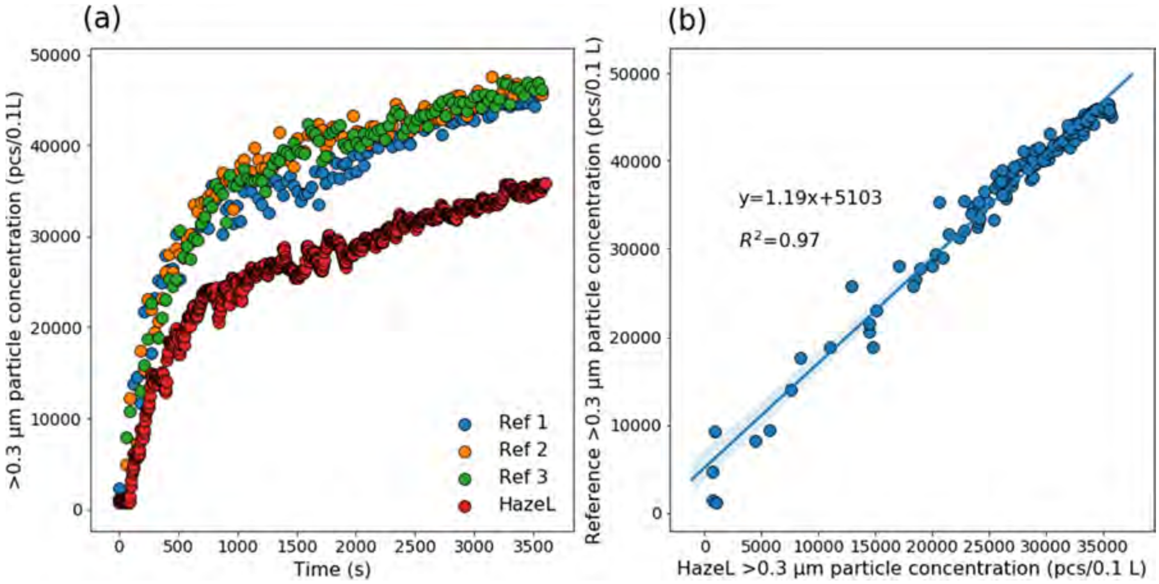

Figure 2. Comparison of the HazeL performance with three reference TSI particle counters.[1−3] (a) Generation of fine NaCl particles approaching steady-state. (b) Linear relationship between output of a HazeL versus the average output of the reference counters (n = 3, the blue line is the regression line with R^2 = 0.97).

Data Download

On start-up, HazeL initializes all sensors and modules, then opens a navigable menu for either data collection or uploading previously collected data. To start data collection, users set the mode of timestamp recording (e.g., manual or automatically through GPS). Once the initial timestamp is collected, HazeL begins sampling particles every 2.5 s and stores these data and associated metadata to the SD card (see Supporting Information S1 on the exact data returned). The data are also sent over USB, providing the option for capturing or displaying a live data stream when connected to a computer. The data download scripts for Mac and Windows are provided at https://github.com/brownby/HazeL. >0.3 μm particle concentrations are displayed on the OLED display every 2.5 s as well. Every 10 s, a line of metadata is stored, including an ISO8601 UTC timestamp, latitude, longitude, altitude, temperature in °C, and pressure in Pa.

■ RESULTS AND DISCUSSION

Performance Testing

Prior to distribution of the HazeL units, system performance was first tested by the teaching staff against the commercially available TSI 9033 Aerotrak Particle Counters (TSI Incorporated, MN, USA). For testing, aerosols were produced from a sodium chloride solution using a TSI 8026 Particle Generator at a constant rate until aerosol levels in a nonventilated room reached steady-state. This particle generator was commonly used for respirator fit testing (based on NIOSH standards) and generates particles with a median diameter of 0.04 μm.[18] The concentration of >0.3 μm aerosols in the room was then measured with the particle generator running constantly for an hour. To check HazeL's sensitivity toward the aerosols, it was placed 1 m above the floor together with the TSI reference particle counters (n = 3). Though HazeL's particle counts were lower than those of the TSI counters, the particle counts agreed well with the trend of the reference (R^2 = 0.97) (Figure 2). Both types of counters had a rapid increase in particle counts at <10 min and showed aerosols leveling off toward steady-state conditions. The measured >0.3 μm salt aerosols also correlated well with PM 1.0 but not directly with PM 2.5 and PM 10, which was expected since only fine particles were produced by the generator (Figure S3). Interday experiments were also performed to ensure robustness of the HazeL platform over a prolonged time period of 96 h (Figure S4). During this test, HazeL measured indoor particle data over a Thanksgiving weekend, showing the influence of cooking on particle counts. This test was done with HazeL connected to a laptop/phone charger via a USB cable.

Lab Logistics

Once the design and manufacturing of the devices were complete, HazeL devices were distributed to the students. To familiarize them with the device, a live demonstration session during lecture was held 1 week before the lab activity. Detailed, recorded instructional videos on data collection and extraction were also uploaded to the course management system. Office hours with the teaching staff were also provided to help students with troubleshooting and any coding related problems. These synchronous and asynchronous resources were offered to ensure students were able to use the devices prior to the laboratory experiment.

The air quality laboratory experiment ran for 2 weeks. In Spring 2021, the first week involved a virtual lab discussion (offered twice at a different time to cover multiple time zones) on air quality, formation of particulate matter, importance of measuring particulate matter, and its relation to toxic biological effects based on the US National Ambient Air Quality Standards (NAAQS).[19] This discussion was followed by a review of the scientific method and on how the students could use its framework in designing their own experiments. Students were instructed to first identify a study question, develop a hypothesis, and discuss these thoughts in a group setting. Then, asynchronously, the students conducted their individual experiments and data collection at home. In Spring 2022, we retained the same experiments but included a calibration step where students compared particle data obtained from different locations using their HazeLs and TSI 9033 Aerotrak Particle

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Counters. An example data set showing the response of these sensors at conditions of low and high particle counts are shown in Figure S5.

The second week focused on data analysis and visualization and included tutorial sessions introducing R for statistical analysis and graphical visualizations (the codes are provided in Supporting Information S2 and can be downloaded directly at https://github.com/mona-dai/HazeL). Students were encouraged to install R on their own computers to avoid any issues surrounding package versions or lack of sufficient computing power. They were also provided remote access to RStudio through a Virtual Desktop Infrastructure service on the Harvard Research Computing cluster. Their analyses were structured to allow the students to explore relationships among particles and a variety of experimental variables in both indoor and outdoor conditions. After downloading raw data from HazeL to saved data files on their computer, all particle data and metadata were converted into a readable format for R to create plots using the *ggplot2* function (R package: tidyverse). The students then determined the mean, median, standard deviation, and 95% confidence interval for total particle counts (>0.3 μm; *gt.3*) to see the differences between two selected sampling sites (*p1*, *p2*). They also visualized these data sets by plotting particle data distribution through histograms (*geom_hist*) and density plots (*geom_density*), as well as checking whether the data followed a normal distribution using the *dnorm(x,df)* function. To test the significant difference of the particle variability between the two sampling locations, students used the *t.test()* function and plotted the *t*-distributions. The students presented their time-series data as a line graph (*geom_line*) to observe the continuous variability of particle concentration at a single location and decay rates after elevated PM values. Data smoothing and filtering were also performed in EPS/ESE 102 using R's *loess()* function and *sm.spline()*, which is a smoothing function in package *pspline*. Finally, the students synthesized their results in a laboratory report (see Text S2 in Supporting Information S1).

After submission of lab reports, a Google forms web survey was used to obtain consent from students to use their data for publication, receive feedback on the lab activity, and understand the impact of HazeL to their learning. In Spring 2022, pre- and postlab surveys was used to gauge students' mastery of the content in the lab activity and the course, in general. This was done in accordance with IRB protocol # IRB21-1139.

Student Experiments

We experienced several pedagogical benefits using HazeL in an asynchronous laboratory. In previous years, students would attend prescheduled lab sections, with 15−18 students per section, and work in small groups of 3−4 to design a simple experiment to measure air particulate matter at locations around campus. Each group would be given a sophisticated research-grade hand-held particle counter, and go out and collect data, and then come back to the lab and download the measurements. With the new HazeL platform, students were able to conduct individual experiments assessing their own particle exposures in areas that interested them. Having their own devices allowed them to make meaningful, quantitative measurements about their immediate surroundings, not only around the campus, but in several US states, and around the world in Israel and Mexico from different environmental conditions.

In both Spring 2021 and 2022, the lab activity addressed the following objectives: (1) observe variability of particulate matter between two different locations, and (2) observe variability of particulate matter over time in a single location. The first objective was accomplished by taking measurements with HazeL at locations near the student's home while the second objective was accomplished by measuring particles inside each student's home over a multiday period. Each objective followed an inquiry-based method[20] which entailed students developing their own hypothesis, experimental design, approach to data analysis and visualization, and hypothesis testing.

The asynchronous lab experiments generated several interesting data sets studying spatial and temporal variations of air quality (Table 1). To understand spatial variations of PM

Table 1. Student Experiment Examples Investigating Spatial and Temporal Variability of Particulate Matter Using HazeL

Spatial	Temporal
Indoor small gym vs large ventilated gym in Israel	Effect of kitchen activity and vents
Different coastal locations	Laundry room
Inside the fridge vs general kitchen area	Dorm room and effect of air purifier
American (AZ) vs Mexican pizza place	Room with a candle and an essential oil diffuser
By a busy street vs by a creek	Release of particles from mint leaves
By a river vs by a park	Activities in a work/study desk
Harvard yard vs square (traffic vs no traffic)	Effect of bathroom activity
Different modes of public transportation (subway vs busway)	Type of food cooked in the kitchen
Coffee shop vs train station	Room while burning sage
Ground floor vs basement	Kitchen and effect of vacuum cleaning
Rural vs suburban environments	Room and effect of opening windows during bad weather

levels, students collected data from two locations for at least 15 min. Some data sets compared the influence of traffic at various locations including busy streets and parks, coastal locations, dorm rooms, train tunnels and busways, and parking basements. Other data sets studied aerosols from gyms, kitchens, coffee shops, restaurants, and zoos. Example student plots are presented in Figures 3 and 4. Student F.P. (Figure 3a) took samples from Harvard Square, a high flow area for pedestrians and vehicles, and found an average of 2174 ± 80 pcs/0.1 L (mean ± standard deviation). This concentration was higher compared to Harvard's quad lawn (a green space adjacent to Harvard Square, 1864 ± 84 pcs/0.1 L), confirming vehicle emissions as a significant source of aerosols. Student E.G. showed that people are more exposed to harmful particles when commuting via underground passenger trains than in buses (Figure 3b), possibly due to accumulation of particles from brakes-wheels-rails interfaces and limited air circulation. The train commute had a mean particle level of 6626 ± 555 pcs/0.1 L, while the bus ride at the same stops had 2068 ± 529 pcs/0.1 L. Performing two sample *t*-tests for these scenarios all resulted in statistically significant results ($p < 0.05$).

To study temporal variations of PM levels, students used HazeL to survey their homes for 24−48 h. Students collected data in locations including the kitchen, and attributed cooking with increased particle counts. They also monitored laundry rooms, study/work rooms, bedrooms, and bathrooms. All

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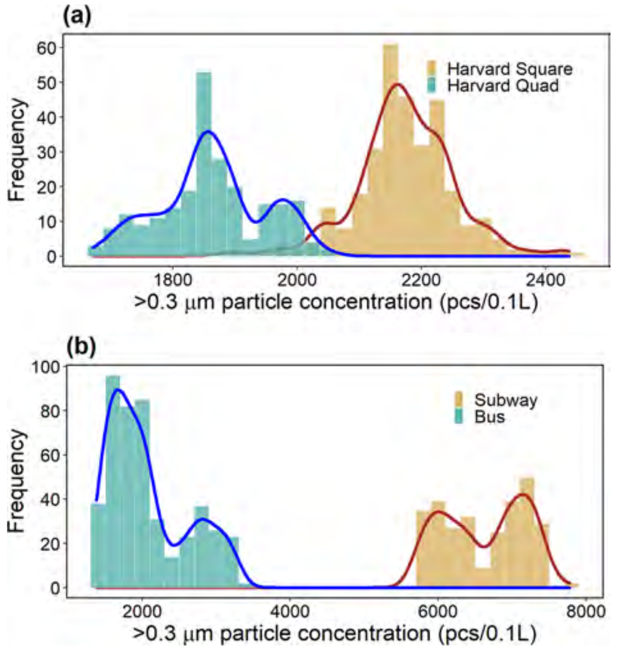

Figure 3. Spatial variability of particle matter over 15 min analysis time per location. The histograms present the distribution of >0.3 μm particle concentrations at (a) Harvard Square and Quad Lawn, and (b) a subway and bus commute. The bars show the frequency of occurrence for each bin of particle concentration. The blue and red lines are density plots.

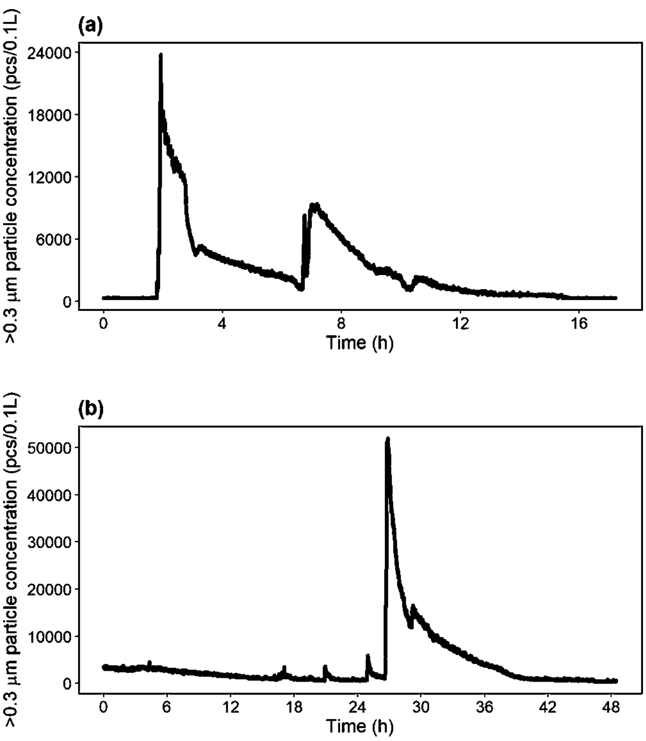

Figure 4. Temporal variability of indoor particulate matter in two locations. The plots show time-series data of >0.3 μm particles in a (a) kitchen and (b) laundry room over a 20–48-h analysis window. The peak at 2 h in (a) occurred while oven-baking two pizzas, and the peak at 7 h occurred while cooking oatmeal on an electric stove. The large spike at 27 h in (b) was caused by exhaust from a clothes dryer.

experiments had varied factors affecting the PM levels (e.g., operating kitchen vents, air purifiers, vacuum cleaning, weather changes, burning events). In Figure 4a, student M.V. noticed that baking pizza and cooking oatmeal on an electric stove could lead to peaks in particle counts that dissipate to background levels only after 8 h. Student E.Z. found that operating the dryer in the laundry room caused a spike in particle counts of up to 50,000 pcs/0.1 L suggesting that dryer exhaust was venting out poorly (Figure 4b).

Student Feedback

Overall, students reported positive experiences with using HazeL (survey results from 35 respondents shown in Figure S6). 86% of the students found HazeL to be a valuable tool for enhancing their learning and skill development in analysis and visualization of data. This supports the significant increase in students' mastery of the content covered in the lab and in the course after the activity (Figure S7). 83% reported that using HazeL reinforced discussions in lecture and 74% preferred the self-directed, project-based approach of the lab. 66% reported increased interest in the field of environmental science and engineering and 69% agreed that the activity made them more aware of their exposure to particulate matter. After the lab, students reported changing their day-to-day activities to include opening windows often to have better air circulation, using kitchen vents during cooking, using an air purifier in common rooms, avoiding heavily polluted areas during runs and commute, and being more aware of building ventilation systems. 51% expressed a desire to learn more about the fundamentals of instrumentation, sensors, and pollutant transport, topics which were not covered in this introductory course. The main issues reported by students were associated with downloading raw data and using R for data analysis, since most of the class did not have prior programming experience. In the next iteration, a web application dedicated for loading the data will be provided for the students and more troubleshooting consultation hours will be offered.

■ CONCLUSIONS AND IMPLICATIONS

Here, we present an instructional guide to manufacture HazeL to study indoor and outdoor air quality. We also described how it was implemented as a tool for a remote lab activity on air quality, which was continued even when classes returned to in-person learning. Using HazeL, students were able to gain direct, hands-on experience on sensors, which otherwise is difficult without advanced instruments in a lab setting. Although the examples shown earlier were from undergraduate courses, HazeL can also be used for student projects at various levels. In Summer of 2021, a high school student used HazeL to investigate air quality in the Bronx Zoo, New York, and an undergraduate student used HazeL for a summer research program studying PM variations in train tunnels and bus platforms in Washington, DC. Another undergraduate student also employed HazeL for a special project on "Fluid Mechanics and Transport Processes" to study diffusion of aromatic compounds caused by slapping mint leaves when preparing a cocktail drink. Use of HazeL can also extend to courses studying particle transport as it relates to airborne disease transmission and applications to COVID-19 public health measures (e.g., importance of ventilation). Apart from these, chemical instrumentation courses may also benefit from this device to demonstrate how to design and build sensors. It can foster collaboration among students, particularly those

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J. Chem. Educ. 2022, 99, 3203−3210

concentrating in electrical, mechanical, and environmental engineering, as HazeL requires a variety of components as discussed above (3D printing, electrical circuit boards, field testing, data analysis).

There are a variety of possible uses for HazeL as a teaching tool, not only for particulate matter detection. Its modular design offers flexibility with the type of sensors to incorporate which is its main advantage over other low-cost commercial particle sensor like PurpleAir[21−23] and Fooboot.[24] Depending on the learning objectives, it can accommodate a maximum of 14 sensors which can lead to an enriched learning experience. For example, multichannel gas sensors for carbon monoxide, nitrogen dioxide, and volatile organic compounds can be added to better understand air pollution in urban areas. For soil and aquatic chemistry, there are available sensors for soil moisture, electrical conductivity, pH, oxidation−reduction potentials, among others. Based on the positive outcomes of the lab, HazeL will be used in environmental engineering courses in future years. For the next iteration, other sensors will be added for the soil chemistry component of the course.

As mentioned previously, HazeL also includes the hardware and programming capabilities of an IoT device. This means that the data collected from the sensors can be sent in real time to the Cloud (i.e., remote servers) for visualization, analysis, as well as for conditional triggers. The ThingSpeak platform from Mathworks is used for this functionality as all Harvard College students have access to Matlab, which is the programming language used for the various IoT actions. Future iterations of activities based on HazeL can utilize the IoT capabilities for experiments where real-time data processing is key. Furthermore, the IoT platform can be programmed to initiate triggers, such as to turn on or off certain sensors or devices attached to HazeL using the real time data being collected. While we believe these features will enable a wider possibility of design projects in the upcoming iterations, there were several challenges in utilizing the IoT features in the current iteration. Besides the broad issues of security concerns of IoT devices,[25] battery life and Internet connectivity were two main challenges we faced. Several research studies have reported using IoT-capable sensors for studying indoor air quality.[26] However, their use in education is still limited.[27]

Overall, this work provides educators a new platform that can be easily adapted to fit their class needs and can be a promising teaching tool to introduce students to the rigor of environmental studies.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.2c00535.

Detailed description of components of HazeL (including 3D printed case, electrical schematic diagram), trial tests, survey results, operational instructions, lab activity, and note to instructors (PDF) (DOCX)

Example R codes for data analysis and visualization (PDF) (DOCX)

Program files (ZIP)

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Notes

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