Indoor Soot Pollution Measurement: Sampled Measurements with Gravimetry and Colorimetric Analysis

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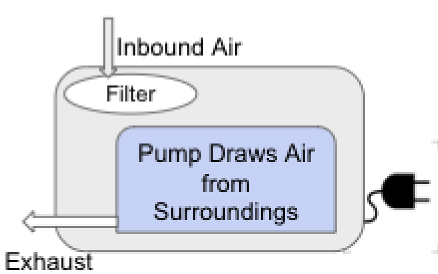
ABSTRACT

Black carbon particulates generated during combustion are major contributors to climate change and adversely affect human health[I]. Prolonged exposure to indoor air pollution from these soot particles can increase the risk of respiratory illness, cardiovascular diseases, and cancer[IV]. The high cost of commercial sensing equipment makes monitoring indoor particulate matter challenging. Earlier studies have extensively examined outdoor air quality, but there is little information on long-term indoor pollution exposure. Using a low-cost aquarium pump, filter paper, and flow control components, this paper presents a simple activity that can be performed by school or college students. The system reliably measured indoor air pollution of 30.24 m^3 after a 40-h deployment in a residential kitchen, allowing comprehensive indoor air quality mapping at reduced costs.

GRAPHICAL ABSTRACT



KEYWORDS

Pump, Exhaust, Filter, Indoor Air, Soot Measurement System

INTRODUCTION

Soot particles generated from the incomplete combustion of hydrocarbons are released from sources such as fires, power plants, factories, and vehicles[I]. Recent studies have identified black carbon (commonly known as soot) to have contributed to 0.04°C of warming since 1750[15]. These particles can absorb sunlight, heating the atmosphere while inhibiting cloud formation and impacting regional weather patterns. Soot is also a strong carcinogen, and a second-class harmful substance that can be carried by winds for thousands of kilometers[14]. Moreover, research indicates that inhaled soot particles can get trapped in the lungs and over 50% of the inhaled particles remaining in the body[I]. This study focused on studying indoor air pollution, specifically soot pollution at a suburban residence in New Jersey.

Although extensive studies have investigated outdoor air pollution, few studies have focused on quantifying exposure to indoor pollutants such as soot, whose long term presence impacts health. Considering people spend maximum time indoors at home, work, or school, the initiated experimental technique aims to demonstrate simple low cost air sampling methods from household materials to quantify indoor particulate matter and soot concentrations. This custom-built air sampling apparatus adapted from a blueprint from the Berkeley National Laboratory's outreach program[III], demonstrates methods that enable quantification of indoor soot pollutants by measuring the airflow rate and mass of collected particles as well as colorimetric analysis and suggests which of these method is best suited, depending on a variety of factors.

The proposed custom-built air sampling apparatus is built with integrated pumps, filters, and flow control components as shown in Figure 6. The change in the filter mass over controlled sampling periods is used to estimate the soot concentration. An important aspect of the methodology was the precision of measurements.

Figure 1. Digital Scale (Source: Amazon)

Figure 2. Air Pump (Source: Amazon)

A high-quality American Weigh Scales Gemini 20 Precision Digital Milligram Scale in Figure 1, is capable of weighing items to an accuracy of 0.001 grams was used to assess the filters. This ensured reliable results when weighing the filters. Throughout the experiment, the JW Pet Company Fusion Air Pump 400 was used to maintain consistent airflow.

Although readily available particulate matter (PM) sensors are convenient for estimating particle concentrations, gravimetric analysis provides significant advantages regarding accuracy, accessibility, and transparency. The method directly measures soot accumulation by quantifying the mass of filter samples, resulting in highly precise and reliable results. The PM sensors, on the other hand, typically measure particle levels indirectly through optical or electrical signals, which can introduce inaccuracies or be susceptible to interference from extraneous factors. Additionally, this activity utilizes simple, common equipment - the JW Pet Company Fusion Air Pump 400 aquarium air pump for airflow and a precision scale for weighing. On a limited budget, this method is easy to set up and replicate. With an accessible, real-world air sampling technique, students and citizen scientists can gain hands-on experience. There is less opportunity for educational exposure when it comes to PM sensors, as they are often proprietary black boxes.

Furthermore, direct physical measurement of particles offers inherent transparency and validation. Alternate gravimetric testing can be used to verify samples independently. Results are therefore more trustworthy. The readings from PM sensors require a calibration assumption and algorithms that are less visually verifiable. For educational activities, gravimetric methodology offers accessibility, transparency, and accuracy, while readily available PM sensors provide convenience.

FLOWCHART

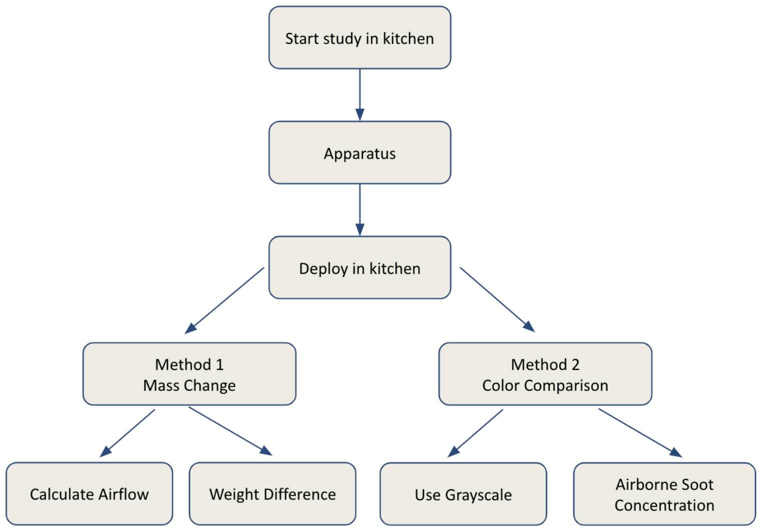


Figure 3. Two techniques for quantifying indoor air pollution

VALIDATION

Two techniques were explored for quantifying the indoor particulate matter using the designed air sampling apparatus via mass change gravimetry and colorimetric analysis.

Mass change gravimetry

Using the mass change method, the particulate concentration was determined by measuring the change in filter mass during sampling and accounting for the total volume of air sampled. Over a 40-hour period, the total airflow was captured, and the soot concentration was determined by dividing the change in mass by the total airflow. The results from this methodology yielded a soot/pollutant concentration of $231.4\mu g/m34\ \mu g\ m^{-3}$ applying Equation 1. The total airflow was found as 200 gal h^{-1} and was converted to $m^3\ h^{-1}$.

$$200\frac{gal}{hour} * 3.78\frac{1ltr}{gal} * \frac{1000\ cm^3}{1ltr} * \frac{1\ m^3}{10^6\ cm^3} * 40\ hours\ = 30.24\ m^3 \tag{1}$$

Here is the step by step breakdown of the calculation:

1. Conversion from gallons to liters: 200 gal/hour × 3.781 ltr/gal
2. Conversion from liters to cubic centimeters: × 1000 cm^3/ltr
3. Conversion from cubic centimeters to cubic meters: ×1m^3/10^6 cm^3
4. Multiplying by the time period (40 hours): × 40 hours

This methodology provides a direct measure of particle mass concentration. In spite of this, ambient conditions may alter the result independent of particulate accumulation. Environmental factors such as temperature, humidity, dust, and vibrations can affect filter mass. The relatively low concentration value obtained highlights the limitations of short-duration sampling. To detect significant mass changes, longer sampling may be necessary for several weeks.

Colorimetric Analysis

Image analysis was used in the colorimetric method to determine the change in filter color before and after sampling. Grayscale pixel intensity was related to deposition densities, which were converted into mass concentrations using total air volume. The 40-h kitchen sample, however, did not show any noticeable color change. This indicated that the deposited particle mass was below the detection limit of colorimetric analysis (approximately $10\ \mu g\ m^{-3}$). When there is a high concentration of pollutants or a long sampling duration, the filter staining can be distinguished visually. The surface area of the filter was calculated using Equation 2:

$$A = \pi r^2 \left(A = \pi * 0.45^2 \right) \tag{2}$$

The value of $\#\mu g$ was calculated using Equation 3.

$$\#\mu g = A * \mu g/cm^2 \tag{3}$$

The concentration of particles in $\mu g/m^3$ was obtained by following Equation 4.

$$\frac{\#\mu g}{\#\ minutes * \frac{L}{minute}} * \frac{1L}{0.001 m^3} \tag{4}$$

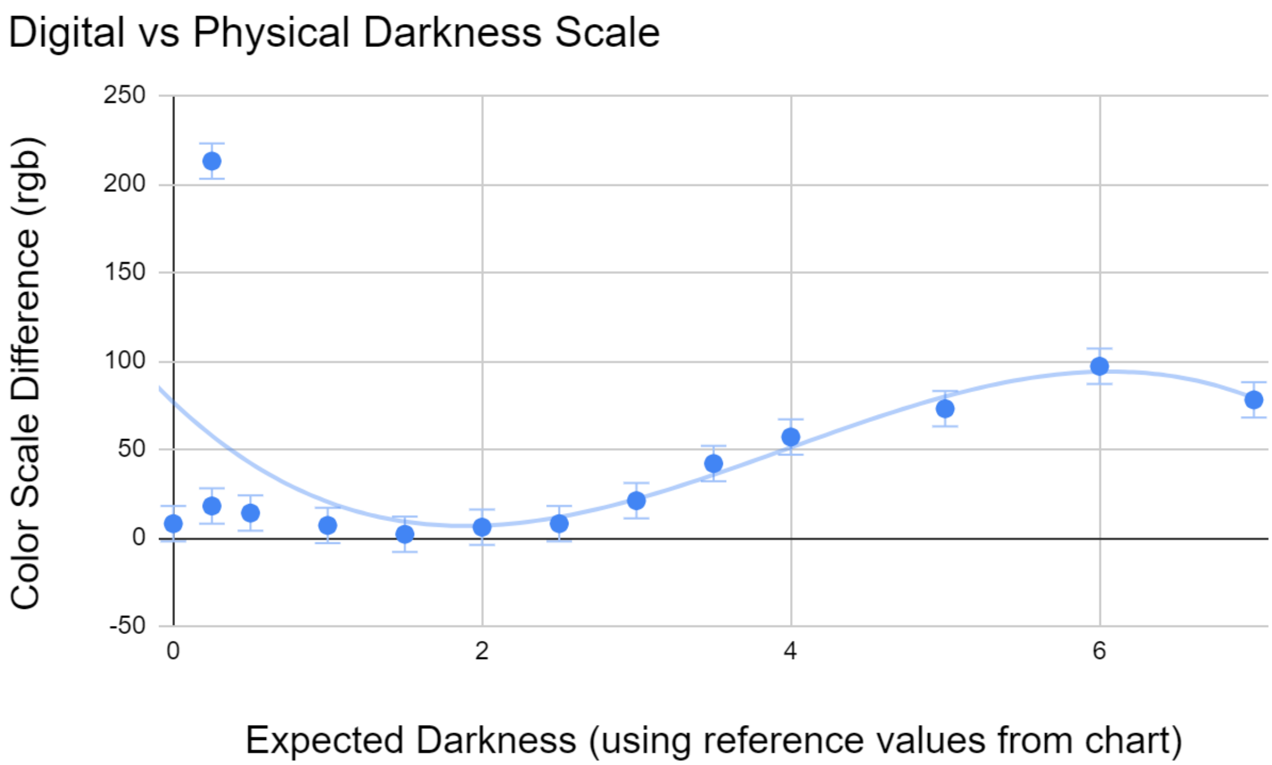


Figure 4. Colorimetric Measurements

In colorimetric analysis, it is crucial to use a digital version of the color comparison chart rather than a printed one. Compared to a printed version of the same scale, the digital darkness scale exhibited a significant difference in RGB values. Since certain gray tones, especially those that are very dark, cannot be reproduced by a printer easily, this difference could be attributed to the printing process. In the figure, the physical darkness scale differed significantly from its digital counterpart at higher expected darkness levels.

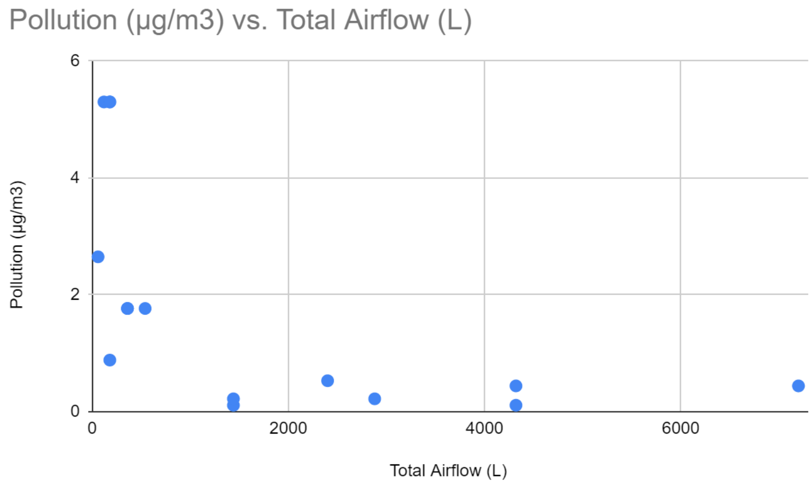


Figure 5. A Comparative Analysis of Mass Change and Colorimetric Measurements

Even at low sampling durations, mass change gravimetry provides a more accurate and quantitative measure of particulate matter concentration than colorimetry. This result was expected since natural gas kitchen ranges do not produce soot. However, environmental variables may influence the results, such as the presence of indoor soot from external fires. While colorimetric analysis is simpler, it lacks sensitivity at trace levels of particulates. For high-pollution sites or large air volumes, it is more suitable. Colorimetric detection for initial mass deposition and gravimetry for final quantification can be combined in a hybrid approach.

Air Measurement System

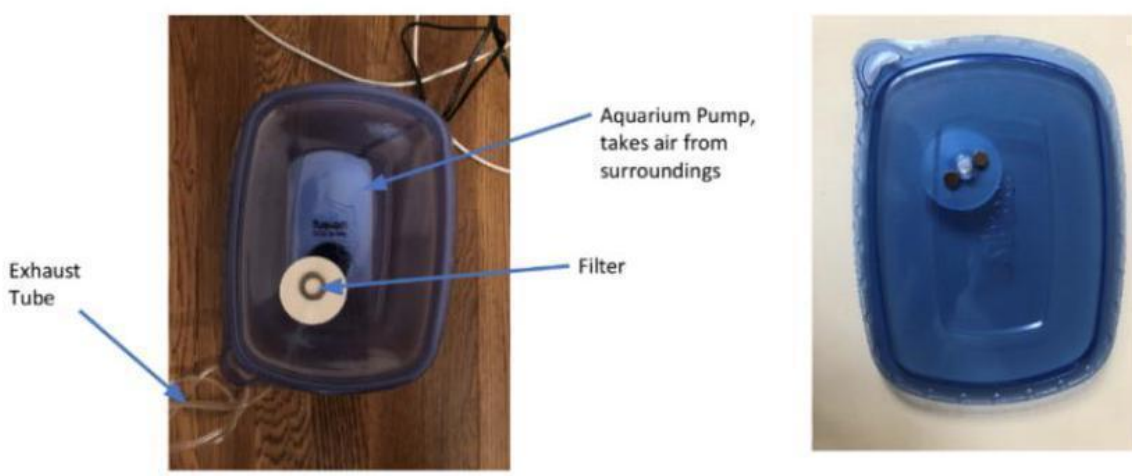


Figure 6. Air measurement system.

CONCLUSION & FUTURE SCOPE

Using a custom-designed gravimetric air sampling system, this activity successfully demonstrated a low-cost method for quantifying indoor particulate matter. Portable and inexpensive, the developed device can be used to assess air quality in residential and workplace settings. Through careful experimental design, it is possible to gain insight into indoor pollution levels and exposure risks. An important highlight was the necessity of sufficient sampling duration with 2 weeks or more of continuous collection for measurable particle deposition.

When comparing gravimetric and colorimetric methods, weighing filter mass changes was more accurate and sensitive, especially at low particle levels. It is important to note, however, that environmental conditions can affect mass measurements. The accuracy of monitoring can potentially be improved through an integrated methodology that utilizes both techniques. In addition, the experimentation and data provide a foundation for extending air quality studies to diverse indoor environments. As a whole, the techniques demonstrated can enable students and communities to assess and mitigate risks associated with indoor air pollution. There could be further studies that consider factors such as humidity and dust that will impact the filter's weight. A box containing the air measurement system should have a side opening that allows air to enter, preventing dust from directly collecting on the filter. In addition, a control filter should be placed inside the enclosed box to account for possible humidity-related weight increases.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.XXXXXXX.

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REFERENCES

1. Lund University. "Half of inhaled soot particles from diesel exhaust, fires get stuck in the lungs." ScienceDaily. ScienceDaily, 27 June 2012.
2. Rissler, J.; Swietlicki, E.; Bengtsson, A.; Boman, C.; Pagels, J.; Sandström, T.; Blomberg, A.; Löndahl, J. Experimental determination of the deposition of diesel exhaust particles in the human respiratory tract. *Journal of Aerosol Science.* 2012; *48*: 18–33.
3. Hansen, T. Berkeley Outreach Program, LBNL Engineering. https://instesre.org/NSFWorkshop/HansenParticulateCollector.pdf (accessed Sep, 2023).
4. American Lung Association https://www.lung.org/clean-air/outdoors/what-makes-air-unhealthy/particle-pollution (accessed Sep, 2023).
5. Monitoring and Modeling of Indoor Air Pollution - NCBI. Retrieved from https://www.ncbi.nlm.nih.gov/books/NBK234059/
6. Assessing Exposures to Household Air Pollution in Public Health Research and Program Evaluation - PMC - NCBI. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4416115/
7. Methods of Measuring and Monitoring Atmospheric Sulfur Dioxide - epa nepis. Retrieved from https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=9100JN56.TXT
8. Combined and modular approaches for multicomponent monitoring of indoor air pollutants. Retrieved from https://www.tandfonline.com/doi/full/10.1080/05704928.2021.1995405
9. Approved Methods for the Sampling and Analysis of Air Pollutants in New South Wales - NSW Government. Retrieved from https://www.environment.nsw.gov.au/resources/air/07001amsaap.pdf
10. Emission of soot particles from the combustion of various fuels in boilers Retrieved from https://iopscience.iop.org/article/10.1088/1755-1315/866/1/012010
11. Short-lived climate pollutants (Black carbon) Retrieved from https://www.ccacoalition.org/short-lived-climate-pollutants/black-carbon
12. Figure 1. Digital Scale. Retrieved from https://www.amazon.com/gp/product/B0012TDNAM
13. Figure 2. Air Pump Retrieved from https://www.amazon.com/gp/product/B0018CDR68