# Household Indoor Particulate Matter Measurement Using a Network of Low-Cost Sensors

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## Abstract

The World Health Organization estimates that 4.3 million deaths globally were attributed to household air pollution in 2012, and particulate matter (PM) with a diameter of 2.5μm or smaller ($PM_{2.5}$) is a significant contributor to household air pollution. Low-cost PM measurements when integrated in a wireless network offer the promise of providing personalized information on indoor concentrations in real time so that individuals may take action. The objective of this study was to (1) deploy a network of research grade instruments and low-cost sensors in a home environment and evaluate their performance, (2) characterize activities and conditions that increase PM concentrations, and (3) identify how these activities affect PM levels in different rooms in a home. The wireless sensor network included low-cost PM sensors, a gateway, and a database for storing data. The low-cost sensors were based on the commercially available Dylos DC1100 Pro (Utah Modified Dylos Sensor) and Plantower PMS sensor (AirU). These were compared to three research-grade instruments – the GRIMM, DustTrak, and MiniVol in two households in Salt Lake City, during summer and winter. The results suggested that the AirU and Dylos-based sensor correlated well with the DustTrak. In this study, cooking (frying) and spraying of aerosol products caused the greatest increase in PM levels in the room of the activity (specifically in the kitchen and bedroom, respectively) as well as in surrounding rooms. The study also found that elevated outdoor PM levels during a cold air pool caused indoor PM levels to increase. In addition, the different PM sources caused different sensor responses. Consequently, obtaining accurate estimates of mass concentration from an indoor environment, with the wide variety of PM sources, would be challenging. However, low-cost PM sensors could be incorporated into an indoor air-quality measurement network to help individuals manage their personal PM exposure.

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# INTRODUCTION

The World Health Organization (WHO) estimates that 4.3 million people die annually from household air pollutant exposure (World Health Organization, 2014), and particulate matter (PM) is one key driver of air pollution's adverse health effects. Particles with an aerodynamic diameter of 2.5 μm or smaller ($PM_{2.5}$) are a particular concern because these particles can penetrate deeply into the lungs and can cause serious health effects, including cardiac arrhythmia, coronary heart disease and premature death (Anderson *et al.*, 2012; Brook *et al*., 2010; Sorensen *et al.*, 2003). Consequently, the WHO and government organizations have set ambient air quality standards for $PM_{2.5}$. For example, the US National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$ are 35 $\mu g/m^3$ (24 hour) and 12 $\mu g/m^3$ (annual average) (U. S. Environmental Protection Agency, 2014). The WHO $PM_{2.5}$ standards are 25 $\mu g/m^3$ (24-hour mean) and 10 $\mu g/m^3$ (annual average) (World Health Organization, 2006). Indoor levels of PM are significant contributors to an individual's exposure because people typically spend up to 90% of their time indoors (Spengler and Sexton, 1983; Zhang and Smith, 2003; Zhu *et al.*, 2015), and PM concentrations indoors can surpass outdoor levels (Klepeis *et al.*, 2001). In addition, individuals with chronic health conditions often spend a greater portion of their time indoors and are more vulnerable to the adverse impacts of indoor PM exposure. Sources of indoor PM include aerosol sprays, cooking, burning candles or heating/cooking with solid fuel, inadequately tuned gas stoves and furnaces, pets, dust mites, cleaning and tobacco smoking. In addition, indoor air is also affected by infiltration of outdoor air (Goyal and Kumar, 2013). Indoor PM concentrations can be affected by infiltration of outdoor air. Depending on the outdoor PM levels, this infiltration can result in increasing or decreasing indoor PM levels (Kumar and Morawska, 2013; Morawska *et al.*, 2001).

Numerous studies have measured PM concentration indoors by pulling air through a size-selective inlet and collecting PM on a substrate/filter that is subsequently weighed (Braniš *et al.*, 2009, 2005;

Fromme *et al.*, 2008, 2007; Hering *et al.*, 2007) or have used passive samplers that rely on particle settling onto a substrate that is subsequently weighed (Amaral *et al.*, 2015; Bo *et al.*, 2017). However, these methods suffer from limitations. First, the substrate/filter measurements are integrated over time (from several hours to several days) and do not capture temporal variations in particle concentration. Second, they are time-consuming to collect and analyze, and results may not be available for several days after sampling is complete (Amaral *et al.*, 2015; Kumar *et al.*, 2016). Third, many of these samplers require a pump, and are bulky and noisy for indoor use. For passive samples that require long sampling times, there is a risk of loss of sampled material (Kumar *et al.,* 2016). Research-grade instruments based on optical detection methods have also been used to measure indoor PM levels (Amaral *et al.*, 2015). They can provide accurate, time-resolved rapid, PM measurements, but the cost for these ranges from $5,000 to $20,000, making them too expensive to deploy many instruments in multiple indoor environments or for use in population-based studies.

Commercially available low-cost PM sensors are becoming more widely available, and with their rapid response they offer the potential for gathering large quantities of high-resolution, spatio-temporal air-quality information in indoor and outdoor environments (Kumar *et al.*, 2016). They typically use light scattering to estimate PM concentrations, and light scattering is a common measurement strategy for research-grade PM monitors. The cheapest PM sensors cost less than $20. Examples include the Shinyei PPD42NS Dust Sensor (Shinyei Corporation), Sharp GP2Y1010 (Sharp Corp.), Plantower PMS series (Plantower Technology), and Honeywell HPM series particle sensor (Honeywell Inc.). These sensors require an interface with an external microprocessor and either a display or a way to transmit data to the user. Adding these features can significantly increase the price, above $100 (i.e., Alphasense OPC, Alphasense). However, once integrated with a microcontroller, these types of sensors are well suited for deployment in a sensor network. Slightly more expensive sensors, costing

between $200 and $500, push their data to the cloud for viewing through a user interface (i.e., Air Quality Egg, Wicked Device, LLC) or an on-screen display (i.e., Dylos monitors/Dylos Corporation, Speck/CREATE Lab, Carnegie Mellon University) (Jovašević-Stojanović *et al.*, 2015). These more expensive sensors may require modifications to allow integration with a sensor network.

However, low-cost PM sensors have their drawbacks. They are not as accurate as gravimetric sampling methods (Dacunto *et al.*, 2013) or reference PM instruments (Manikonda *et al.,* 2016). These sensors can also be affected by humidity (Wang *et al.,* 2015), temperature (Gao *et al.*, 2015) and the same set of sensors can perform inconsistently (Gao *et al.*, 2015; Zikova *et al.*, 2017). In addition, most sensors lack guidance on deployment and calibration data under different conditions. Furthermore, light-scattering PM measurements require regular calibration and an appropriate correction factor (CF) for the aerosol types (Dacunto *et al.*, 2015) and environmental conditions under which the sensors are operating (Kelly *et al.*, 2017; Sayahi *et al.*, 2019). ~~some type of scaling or correction factor for accurate measurements of certain aerosols~~, and low-cost PM sensors may be more sensitive to particle properties than research-grade monitors (Kelly *et al*., 2017). Also, laboratory performance observed by these sensors are often not reproducible under field conditions, where they exhibit lower correlations with reference instrumentation (Castell *et al*., 2017). In spite of these limitations, the sensors can provide valuable information on relative levels of PM, aid in estimating personal exposure and help identify strategies for reducing these exposure levels. For example, real-time monitoring can aid health researchers in determining which measures, e.g., maximum 10-minute concentration, are most relevant to health outcomes. They are also valuable for development of intervention measures and for meaningful public health metrics, which are accessible to the general public.

Several studies have evaluated the performance of low-cost optical PM sensors in laboratory settings and found moderate to strong correlations with reference instruments, which include Dylos vs. TSI