FIELD APPLICATIONS OF LOW-COST AIR QUALITY MONITORS FOR $PM_{2.5}$ STUDIES

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science in

Civil and Environmental Engineering

at the

UNIVERSITY OF WISCONSIN-MADISON

May 2018

FIELD APPLICATIONS OF LOW-COST AIR QUALITY MONITORS FOR $PM_{2.5}$ STUDIES

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Acknowledgments

I would like to offer special thanks to my advisor, Professor James Jay SCHAUER for his cooperation, support, technical assistance and boundless help during my education and research at the University of Wisconsin-Madison. I also would like to express my deep appreciations to my parents; Vural OZLER, Semra OZLER, and my brother; Melih OZLER who have supported and encouraged me to move forward in my career.

My sincere gratitude to University of Wisconsin-Madison staff and students who helped me during my education and research especially Alexandra LAI and Muge KAFADAR for their limitless helps, patience, and supports, Michael R. OLSON for sharing his technical knowledge, Christopher WORLEY for his countless logistic supports and helps, Evan CORY for the linguistic help to improve this manuscript, Ghassan Al GHASSANI and Ahlam Al HANAI for their supports, helps and arrangements in Muscat, OMAN. I would not be able to complete my work without their help and cooperation. Many thanks to Associate Professor Ross EDWARDS and Assistant Professor Matthew GINDER-VOGEL for willing to be my thesis defense committee members. Moreover, I gratefully acknowledge the input of many scientists and engineers in providing useful information and research results in the manuscripts that I cited.

Finally, I am grateful to The Turkish Republic-Ministry of National Education and The Turkish Republic New York Turkish Education Attaché for their financial support of my tuition and other expenses during my education in the United States.

Dedication

This thesis is dedicated to the pale blue dot which is the only home we've ever known on a mote of dust suspended in a sunbeam and the science which is the only way to discover the truth.

Figure 1. The Pale Blue Dot.
Source: https://www.imgbase.info/images/safe-wallpapers/space/earth/23308_earth_the_pale_blue_dot.jpg

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Abbreviations

ARMs	Approved Regional Methods
CIA	Central Intelligence Agency
CO	Carbon monoxide
EU	The European Union
FRMs	Federal Reference Methods
FEMs	Federal Equivalent Methods
FMSs	Fixed Monitoring Stations
HSE	Health, Safety & Environment
IHME	The Institute for Health Metrics and Evaluation
NAAQS	National Ambient Air Quality Standards
NCSI	National Center for Statistics and Information
NO_2	Nitrogen dioxide
OECD	The Organization for Economic Co-operation and Development
OWiD	Our World in Data
O_3	Ozone
Pb	Lead
QAQC	Quality Assurance and Quality Control
SO_2	Sulfur dioxide
UN	The United Nations
US EPA	The United States Environmental Protection Agency
PKU	Peking University
$PM_{2.5}$	Particulate matter that has a diameter of less than 2.5 micrometers
PM_{10}	Particulate matter that has a diameter of less than 10 micrometers
TEOM	Tapered Element Oscillating Microbalance
WHO	The World Health Organization

Abstract

Air pollution has become a pressing issue in today's society because of its significant effects on humans, animals, plants, air quality, climate, and the wider environment. Most urban areas are associated with one or more air pollutants which are emitted from local or regional pollution sources including vehicle exhausts, fossil fuels using in energy production, emissions from industrial and mining activities, agricultural and construction operations, household usage of chemicals and materials, and natural causes. Most personal exposure studies are focused on local environments and short-term periods. Previous controlled experiments and studies were done in a small number of designated areas in cities. One of our research studies used time-based activity data; 3 main and 17 sub-microenvironments were applied over 37 days-long research while traveling through Southeast Asian countries. In this study, personal exposure of $PM_{2.5}$ for a traveler was monitored using an assembled low-cost monitor with Plantower PMS 3003 $PM_{2.5}$ sensor which has a light-scattering principle. All time-based activity data was recorded with a smartphone whenever microenvironments changed during the study period. The goal of this study was to understand more about the personal exposure to $PM_{2.5}$ related air pollution in the global travel environment as a traveler and to understand how an individual's activity and location impact $PM_{2.5}$ exposure. Another study focused on deploying 10 low-cost monitors which had Plantower PMS 3003 $PM_{2.5}$ sensors in different areas of Muscat, OMAN, includes both in indoor and outdoor microenvironments. This research was the first study used low-cost monitors to study the spatial distribution of $PM_{2.5}$ concentrations in Muscat. In this study, having various $PM_{2.5}$ concentration datasets helped us to understand the ambient pollution levels and personal exposure to $PM_{2.5}$ related air pollution in Muscat, OMAN.

According to the results from the Southeast Asia study, the personal $PM_{2.5}$ exposure varied in the categorized microenvironments. Port/Station (outdoor) and Café/Pub/Restaurant (indoor-outdoor) were the most polluted microenvironments with 32.8 and 29.6 $\mu g/m^3$ 1-hour mean $PM_{2.5}$ concentration, respectively. Market/Shopping Mall (indoor), Street (outdoor), and Cable Car/Metro/Tram (vehicle) were also concerning microenvironments with 19.3, 19.3, and 18.9 $\mu g/m^3$ 1-hour mean $PM_{2.5}$ concentrations,

respectively. Passenger Car microenvironment had the lowest 1-hour mean $PM_{2.5}$ concentration of 2.3 µg/m^3 which agrees with some other studies on transportation microenvironments in the literature. According to the results from the Muscat, OMAN study, 1-hour mean $PM_{2.5}$ concentrations for all low-cost monitors ranged from 13.5 to 21.0 µg/m^3 and the average 1-hour mean $PM_{2.5}$ concentration was 17.4 µg/m^3.

1. INTRODUCTION

Cities, urban agglomerations with more than 1 million inhabitants, have become very popular places for people to live. A rising demand for workforce in facilities, security, health care and employment has been the driving force of increasing urbanization (Kanakidou et al., 2011). According to United Nations' (UN) "The World's Cities in 2016" data booklet, it was estimated that 54.5% of the world population lived in urban settlements This number was projected to rise to 60% of the total world population living in urban environments by 2030 (UN, 2017). According to the same booklet, there were 512 cities with at least 1 million inhabitants and according to another statistical data, there were 548 cities by the beginning of 2017 (UN, 2017; City Population, 2017). It was also projected in the booklet that 662 cities would have at least 1 million residents by 2030 (UN, 2017). A more detailed picture of global city population growths from 1950 to 2030 is shown in Figure 2.

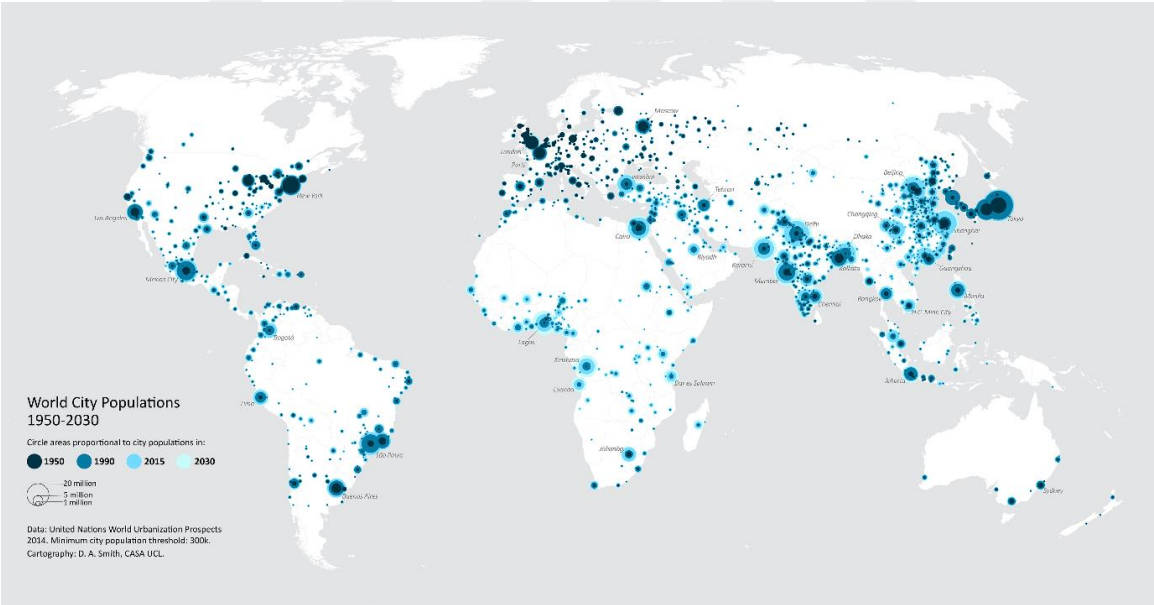

Figure 2. World city populations between 1950 - 2030. Source: http://i.imgur.com/Rd0WPqu.png

Within the last two decades, urban air pollution from large cities has been recognized as one of the world's most concerning environmental issues (Kocak et al., 2011; Yusuf et al., 2008). Most developing countries, following a general trend, have experienced rapid growth including urbanization, urban sprawl, vehicle ownership, and industrialization which is reflected in pollutant emissions to the atmosphere. Urbanization not only affects

the nearby landscape, air quality, regional climate and ecosystems of the polluting cities but also affects areas downwind of these regions despite recent improvements in air pollution science, air pollution control technologies, and public awareness (Molina et al., 2004). Air pollution remains a massive challenge due to continuing uncontrolled emission discharges, inadequate environmental regulations, poor governmental control mechanisms, individual consumption behaviors, and rebound effects of technological improvements for many city dwellers and travelers (Akimoto, 2003). A more detailed picture of annual mean $PM_{2.5}$ concentration from 2008 to 2015 is shown in Figure 3.

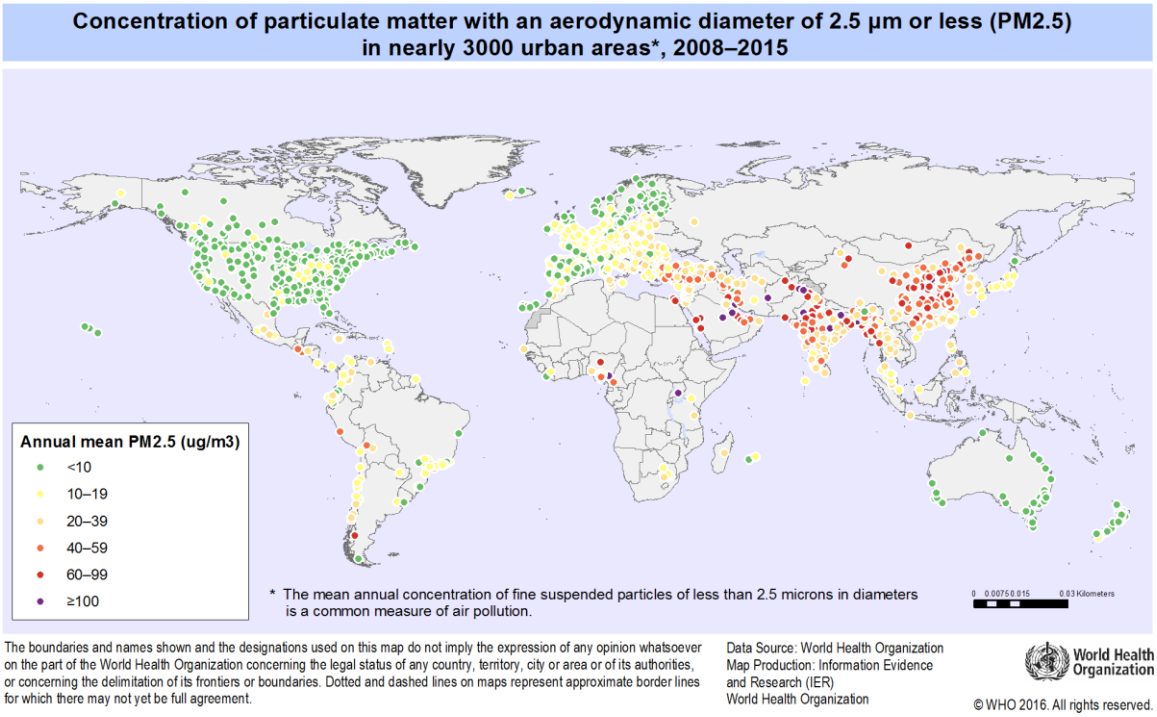

Figure 3. The concentrations of $PM_{2.5}$ in nearly 3,000 urban areas (2008 - 2015).
Source: http://gamapserver.who.int/mapLibrary/Files/Maps/Global_pm25_cities.png?ua=1

As seen in the WHO dataset, there are significant differences in $PM_{2.5}$ concentrations between countries and regions of the world. These $PM_{2.5}$ concentrations are measured using a combination of satellite observations, global air transport models, local meteorological conditions, and local ground measurements if available.

Table 1. $PM_{2.5}$ standards from selected countries.

Countries	Concentration (µg/m3)	Averaging Period	Countries	Concentration (µg/m3)	Averaging Period
Australia	25	24 hours	S. Korea	50	24 hours
	8	1 year		25	1 year
WHO	25	24 hours	Thailand	50	24 hours
	10	1 year		25	1 year
Canada	28	24 hours	EU	-	24 hours
	10	1 year		25	1 year
The U.S.	35	24 hours	India	60	24 hours
	12	1 year		40	1 year
Singapore	35	24 hours	China	75	24 hours
	15	1 year		35	1 year
Japan	35	24 hours	Russia	100	24 hours
	15	1 year		35	1 year
Mexico	45	24 hours			
	12	1 year			

Moreover, WHO states that 92% of the world's population lives in cities and metropolises where $PM_{2.5}$ concentration levels exceed the WHO suggested $PM_{2.5}$ concentration limits which are 10 µg/m^3 annual mean and 25 µg/m^3 24-hour mean (WHO, 2012). Those limits are suggested as guidance to reduce the health impacts of air pollution, but they are not legally binding policies. Most of these countries don't have any regulations related to $PM_{2.5}$. Some countries regulate $PM_{2.5}$ with higher concentration values than WHO's guidelines; this makes it difficult for some cities to comply with the WHO's ambient air quality guidelines (Molina et al., 2004; Sharma et al., 2013). Reported measurements from those cities far exceed WHO's guidelines, resulting in millions of premature deaths (Lim et al., 2012). $PM_{2.5}$ standards from selected countries around the world are shown in Table 1. Australia, for example, set national standards for annual mean $PM_{2.5}$ to not exceed 8 µg/m^3, which is by far the strictest national limit worldwide.

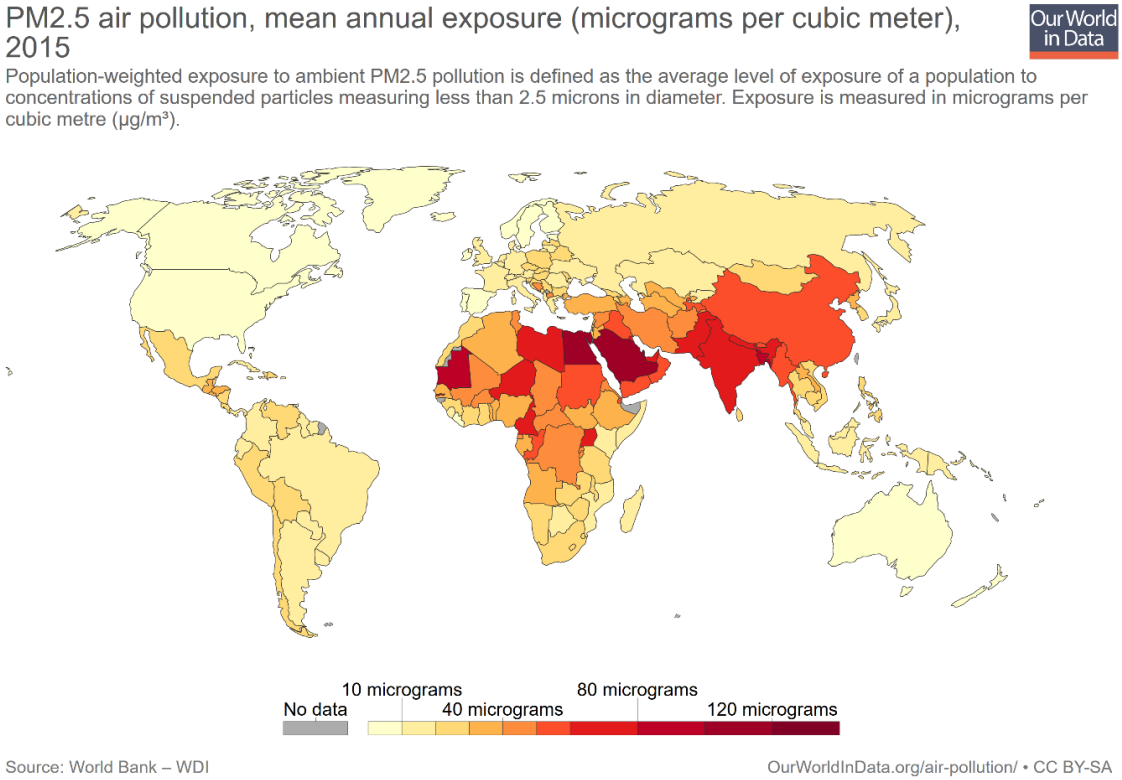

Figure 4. Ambient $PM_{2.5}$ concentrations in 2015.
Source: https://ourworldindata.org/grapher/PM25-air-pollution?overlay=download

There is a large variation in $PM_{2.5}$ exposure across different countries and continents. In 2015, countries across Europe, North America and Oceania had levels of 5 – 10 µg/m^3. This was roughly 15 – 20 times smaller than concentrations in Egypt and Saudi Arabia which topped levels over 100 µg/m^3 (OWiD, 2018). The highest annual average urban $PM_{2.5}$ concentration is 127 µg/m^3 in Saudi Arabia and the lowest average urban $PM_{2.5}$ concentration is 5 µg/m^3 in New Zealand and Brunei Darussalam. In addition to that, only 19 countries comply with WHO's suggested annual mean $PM_{2.5}$ concentration limits. The remaining 160 countries (there are 15 countries without any $PM_{2.5}$ measurement/data) exceed those levels, ranging from 11 to over 100 µg/m^3 (WHO, 2012). It is not surprising that $PM_{2.5}$ related air pollution is a global environmental health problem that affects people worldwide, but low-income and middle-income countries experience this burden more than high-income countries (Figure 4).

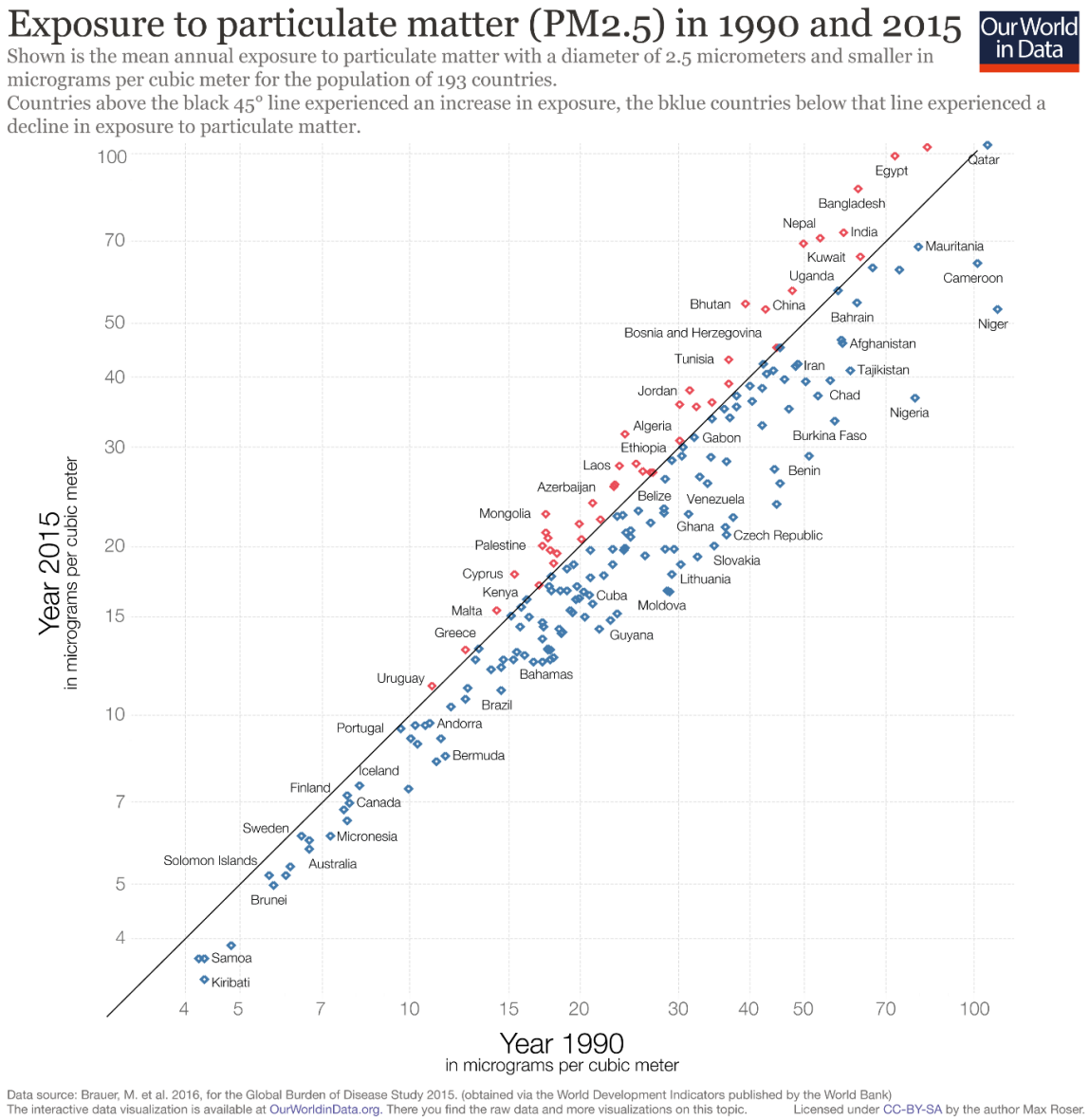

Figure 5. Exposure to $PM_{2.5}$ in 1990 and 2015.
Source: https://ourworldindata.org/wp-content/uploads/2017/04/PM2.5-air-pollution-1.png

Figure 5 shows the exposure to $PM_{2.5}$ in 1990 and then 25 years later in 2015. All countries below the 45° latitudinal line, which are colored blue in the visual, experienced a decline in particulate matter exposure (OWiD, 2018).

A new conceptual framework about Earth systems, planetary boundaries, was developed by a group of environmental scientists in 2009 (Rockström et al., 2009). They identified nine planetary boundaries that must not be surpassed in order to maintain global sustainability. These boundaries create a safe operating space for humanity with respect to the functioning of Earth systems; they are summarized in Figure 6. It is believed that

exceeding one or more planetary boundaries may be deleterious or even catastrophic due to the risk of triggering non-linear, abrupt environmental change from continental to planetary-scale systems (Rockström et al., 2009; Steffen et al., 2015). Atmospheric aerosol loading is one of the most important subjects in the planetary boundaries report because of the influence of aerosols (suspended particles in the atmosphere) on climate systems and their adverse acute and chronic effects on human health (Knibbs et al., 2010; Rockström et al., 2009; Steffen et al., 2015). Although it is hard to determine the exact effects and mechanisms of atmospheric aerosol loading due to the complex composition of particles and gases that are involved in aerosol production, their atmospheric chemistry, and the spatial and temporal dynamics of pollutants.

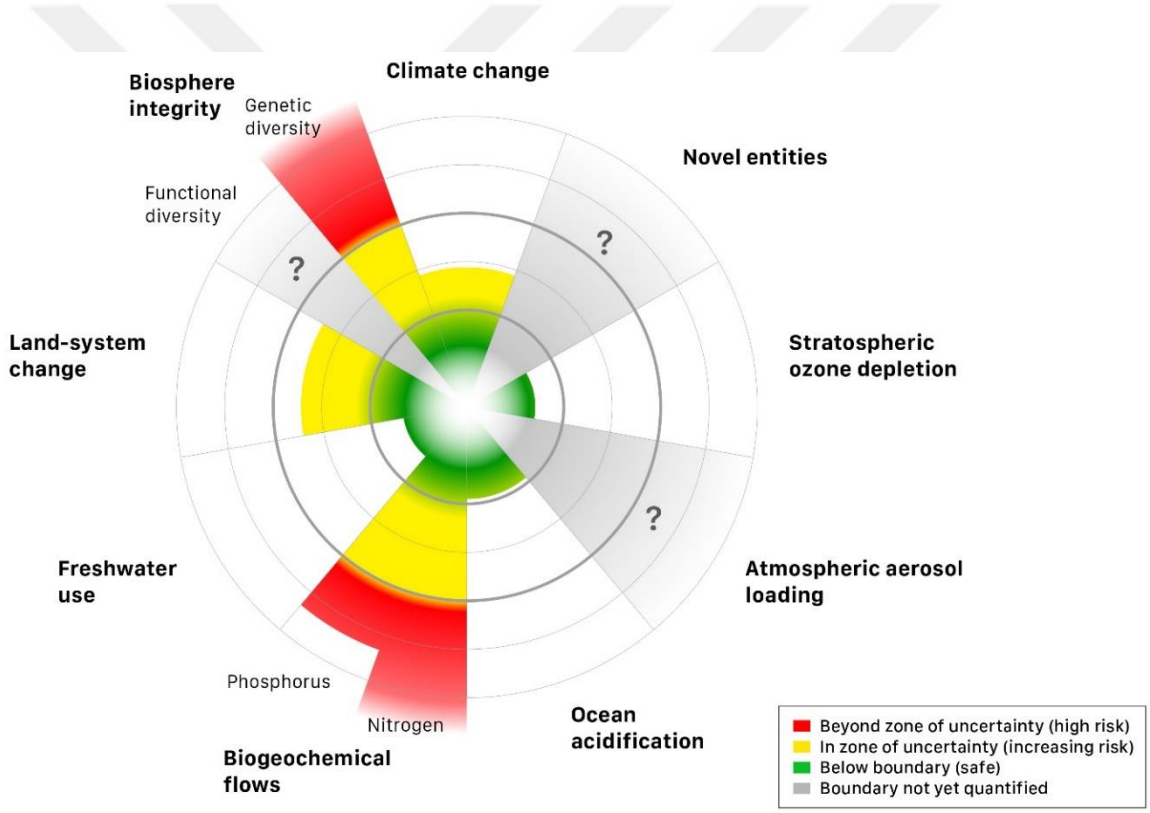

Figure 6. Nine planetary boundaries.
Source: https://kislingjeff.files.wordpress.com/2017/01/planetaryboundaries.jpg

Long-term exposure of $PM_{2.5}$ has been associated with allergies, respiratory diseases, cardiovascular problems and lung cancer; these health outcomes result in increased mortality, morbidity, and hospital admissions (Kingham et al., 2013; Wang et al., 2011). A summary of the health effects of $PM_{2.5}$ exposure is shown in Figure 7. As stated in Steinle's study, controlling air pollution not only directly reduces adverse health effects

but also increases general well-being, quality of life, public health and can have positive impacts on the environment in those countries and regions (Steinle et al., 2015).

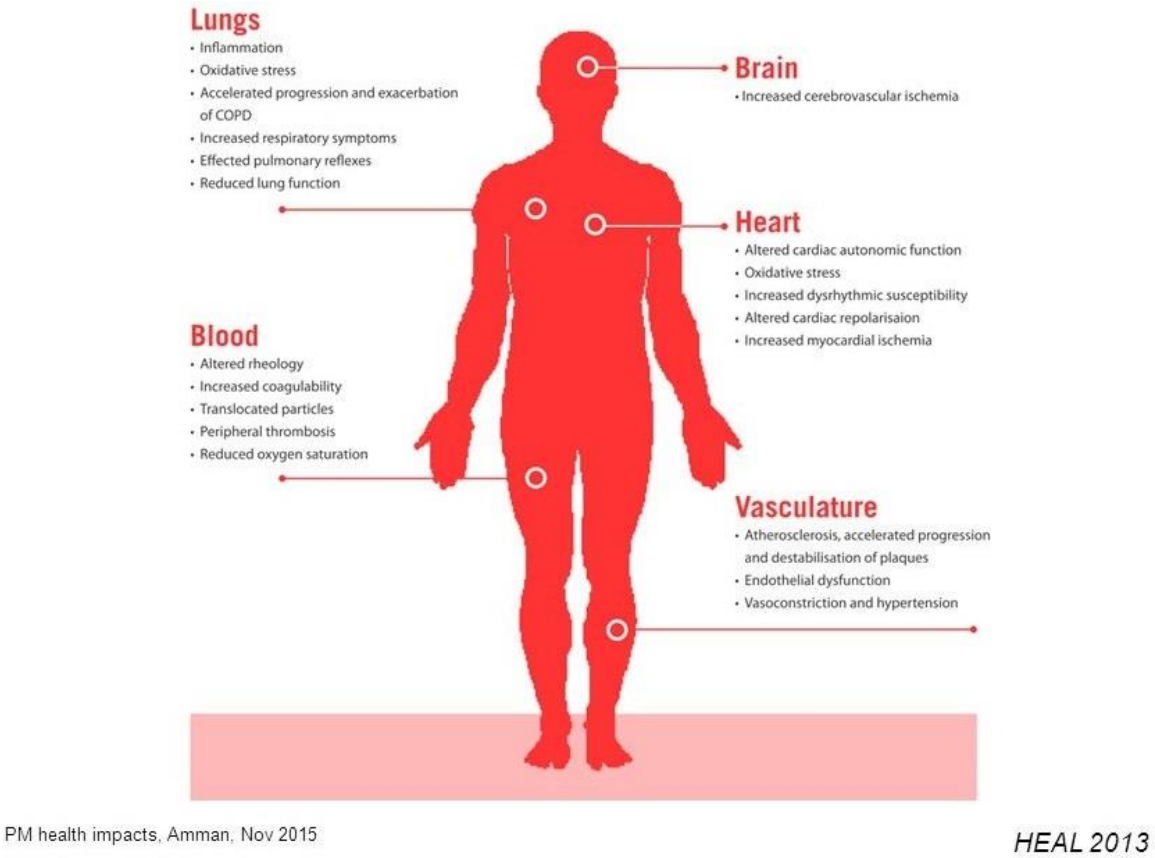

Figure 7. Health effects of $PM_{2.5}$ exposure. Source: http://slideplayer.com/slide/8997353/

The Global Burden of Disease study showed the significant role of air pollution as a global player, placing it among the top ten risks factors faced by human beings (Lim et al., 2012). 20 leading risk factors, including air pollution, are shown in Figure 8 with percentages of global disability-adjusted life-years for men (A), women (B), and both sexes (C). According to the summary report of WHO's "Burden of Disease", 4.3 million deaths globally were attributable to household air pollution and 3 million deaths were attributable to ambient air pollution in 2012 (WHO, 2012). According to the Institute for Health Metrics and Evaluation (IHME)'s dataset which is shown in Figure 8, it was estimated that outdoor air pollution resulted in 4.2 million deaths in 2016; this represents an increase from 3.4 million in 1990. Overall, the majority of pollution-related deaths are in South Asia, East Asia, and Southeast Asia which alone accounted for nearly 3 million deaths in 2016 (OWiD, 2018). Moreover, as stated in Giannadaki's study, the global premature mortality

by $PM_{2.5}$ was estimated at 3.15 million/year in 2010, with China ranking highest, followed by India, Pakistan, Nigeria, Bangladesh, Russia, and the United States (Giannadaki et al., 2016). These studies show that $PM_{2.5}$ is a global actor and responsible for millions of premature deaths. Different results within studies are present due to use of different models that have various health risk function and concentration-response factors, various trends in $PM_{2.5}$ concentrations, and significant population increase within those years.

A ‘death’ from air pollution is defined as someone who dies earlier than would be expected in the absence of air pollution. In many cases, air pollution exacerbates pre-existing cardiorespiratory illnesses and other air pollution-related problems in the human body. Researchers can link pollution concentrations to health risks and mortality by using empirical exposure-response relationships and their relation to mortality rates, complex model studies, and calculations (Cohen et al., 2017).

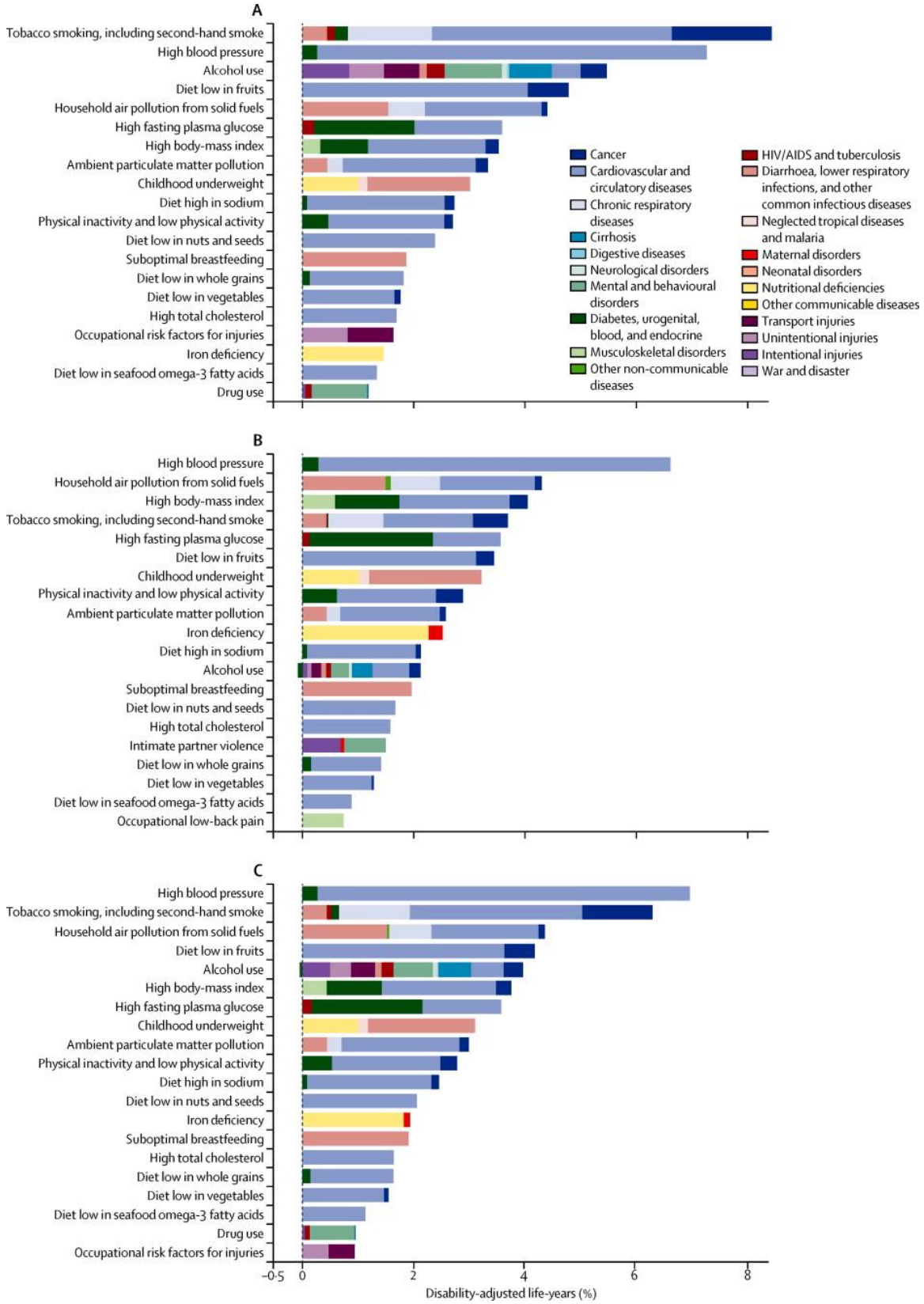

Figure 8. The burden of disease attributable to 20 leading risk factors in 2010, expressed as a percentage of global disability-adjusted life-years. For men (A), women (B), and both sexes (C). Source: http://www.thelancet.com/cms/attachment/2017336186/2037711474/gr2.jpg

Figure 9 shows the absolute number of deaths attributable to outdoor air pollution by country from 1990-2016. This is different from annual deaths; the absolute number of deaths is a function of three variables: the death rate, the population size, and the age demographic of the population. At the annual level, the pollution-related deaths are dominated by China and India, each with between 1.1-1.2 million deaths in 2016 (OWiD, 2018).

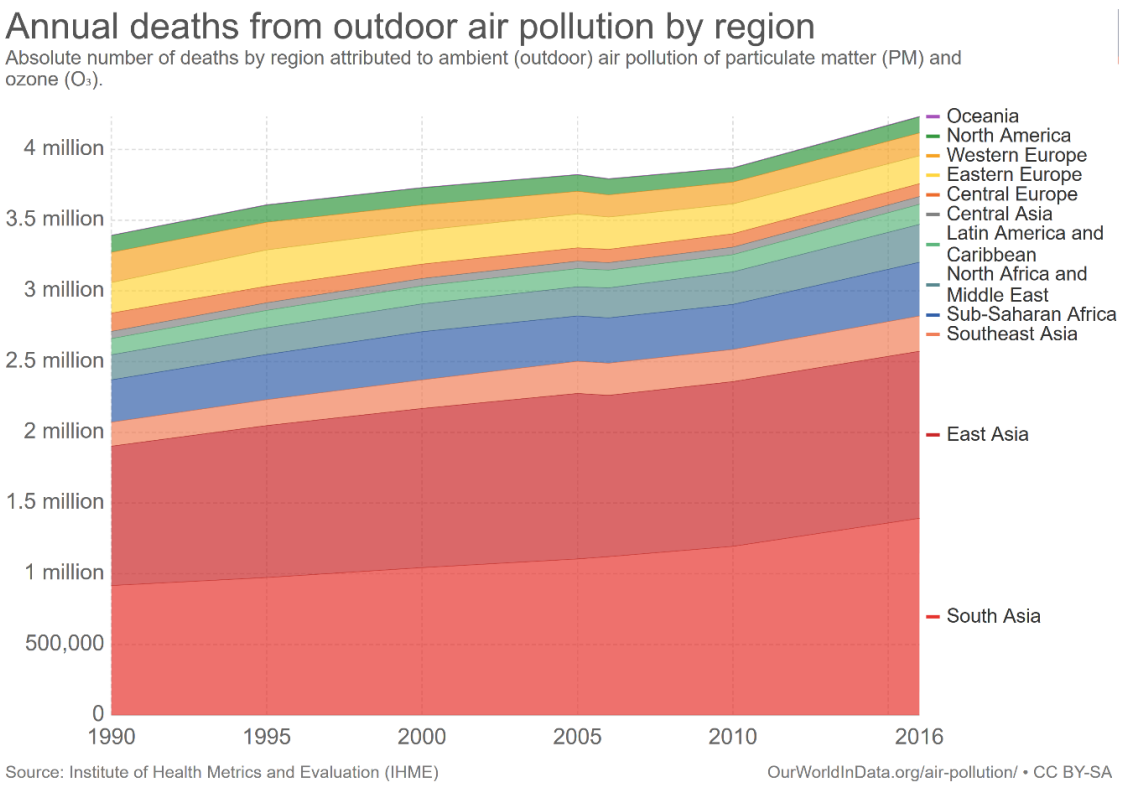

Figure 9. Annual deaths from outdoor air pollution by region.
Source: https://ourworldindata.org/grapher/annual-deaths-from-outdoor-air-pollution-by-region

Figure 10 shows the death rate (per 100,000) from O_3, PM, and indoor pollution from 1990 to 2015. At the global level, the death rate from O_3 exposure is small (less than 5%). Rates of PM and indoor pollution exposure are nearly equal. The relative contributions of the three sources vary between country. Most high-income countries experience negligible impact from indoor fuel use, in contrast to many low-to-middle income countries where household pollution is dominant (OWiD, 2018).

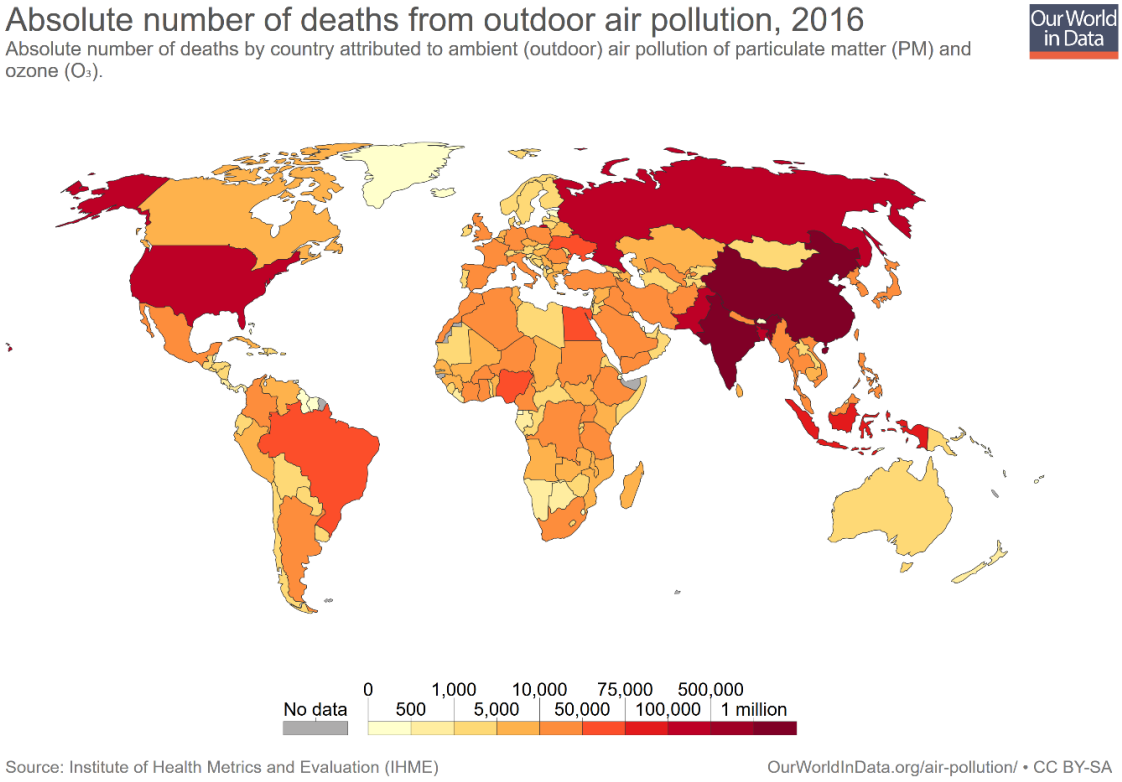

Figure 10. The total number of deaths from outdoor air pollution in 2016.
Source: https://ourworldindata.org/grapher/absolute-number-of-deaths-from-outdoor-air-pollution

Figure 11 and Figure 12 focus on the death rate (per 100,000 people) from $PM_{2.5}$ by country from 1990 to 2015. Death rates from $PM_{2.5}$ have shown a general decline over the last few decades for developed and developing countries. For many countries, the death rate has declined by more than 50 percent even in countries with a growing absolute number of deaths such as China and India. The increase in an absolute number of deaths from $PM_{2.5}$ is attributable to changing population structures (either a growing and aging population) rather than an increased individual risk of mortality. The decline in death rates in higher-income nations appears to be slowing; however, the risk of mortality from $PM_{2.5}$ is still markedly lower than in most low-to-middle income countries. In 2015, the death rate from $PM_{2.5}$ in Australia and New Zealand (the lowest globally, at 9 per 100,000 people) was nearly fifty times lower than in Afghanistan (the highest globally, at 427 per 100,000 people). In most high-income nations, less than 30 people for every 100,000 died prematurely from $PM_{2.5}$ (OWiD, 2018).

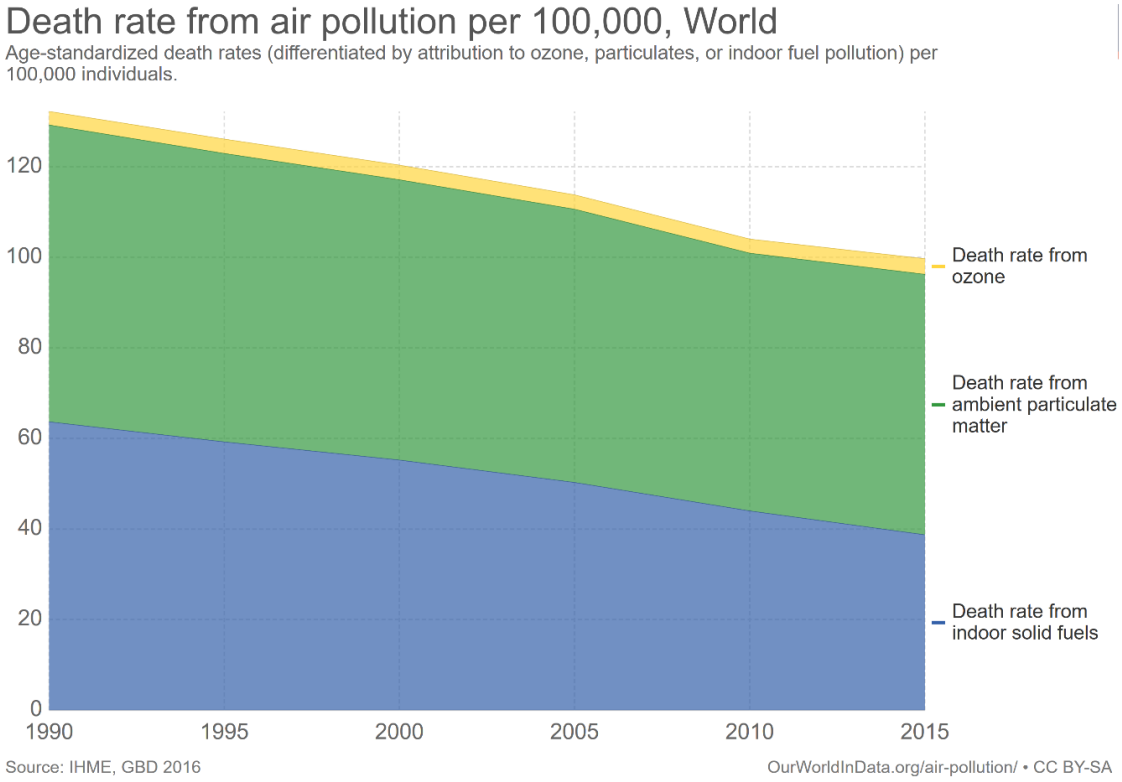

Figure 11. The death rate from O_3, ambient $PM_{2.5}$, and indoor related air pollution.
Source: https://ourworldindata.org/grapher/death-rate-by-source-from-air-pollution

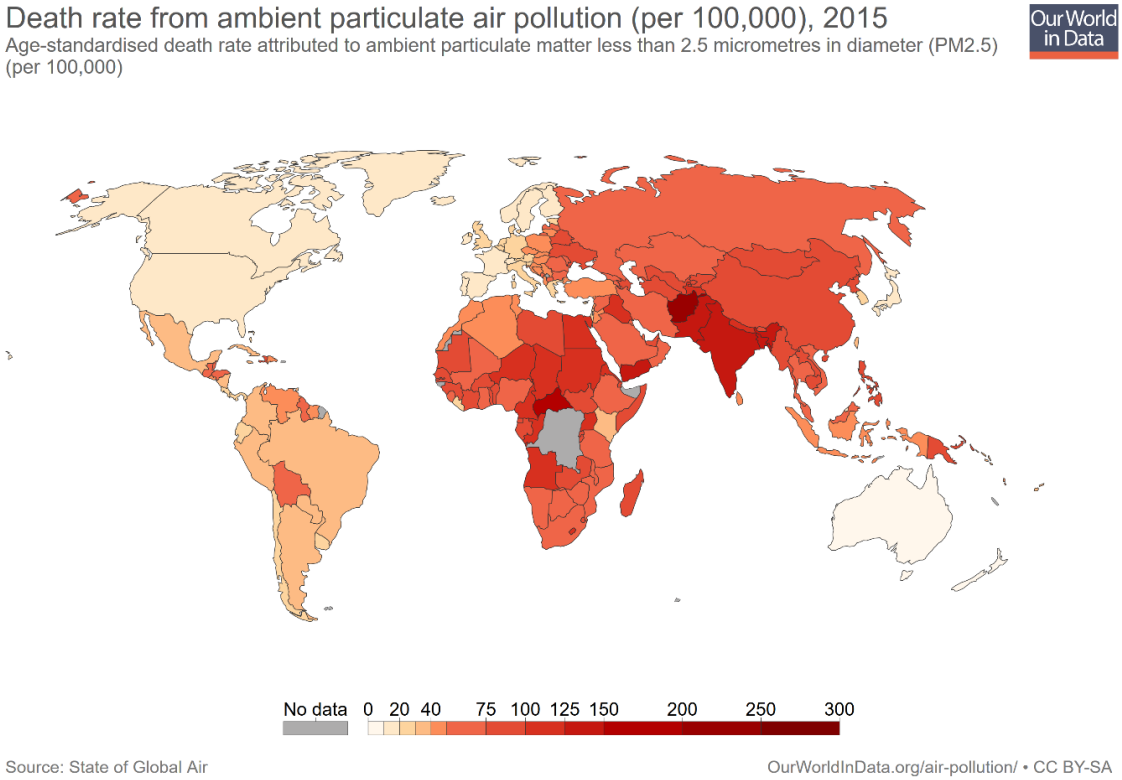

Figure 12. The death rate from ambient $PM_{2.5}$ in 2015.
Source: https://ourworldindata.org/grapher/death-rate-from-ambient-particulate-air-pollution-per-100000?tab=map&year=2015

In general terms, the death rate from $PM_{2.5}$ is higher in countries that have higher levels of pollution and is lower in countries that have lower levels of $PM_{2.5}$ concentration. It is true with most European, North American and Latin American countries cluster near the origin at low pollution levels and low death rates. Nearly all countries with either a high death rate or high $PM_{2.5}$ concentration (or both) are in Africa or Asia. Other external factors are also important such as overall developmental indicators; GDP per capita, quality of life, overall health and healthcare quality. This explains why Qatar, Saudi Arabia, Oman, Kuwait, and the UAE have a comparatively lower risk of premature death, despite having high levels of $PM_{2.5}$ and why Afghanistan and the Central African Republic have a very high death rate, despite having mid-range levels of $PM_{2.5}$ concentration in Figure 13 (OWiD, 2018).

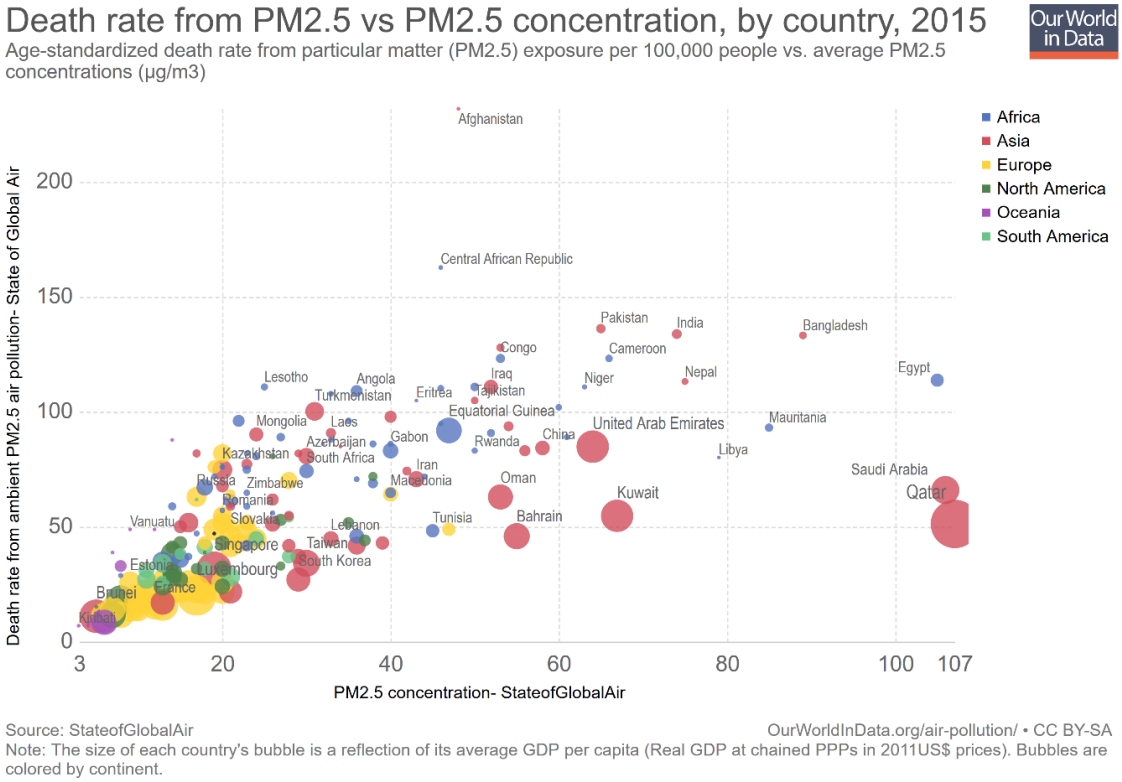

Figure 13. The death rate from ambient $PM_{2.5}$ in 2015.
Source: https://ourworldindata.org/grapher/death-rate-from-pm25-vs-pm25-concentration-by-country

3.15 million premature deaths were estimated in Giannadaki's study due to long-term exposure to $PM_{2.5}$ in 2010 which is summarized in Figure 14 (Giannadaki et al., 2016). This study utilized an interesting approach called sensitivity calculation, which allowed setting different upper limits for the annual mean $PM_{2.5}$ concentration. They used their sensitivity calculation to estimate potential reductions in mortality rates by limiting annual mean $PM_{2.5}$ concentration to 25 µg/m^3, following the EU standard and 12 µg/m^3, following the United States standard which is listed in Table 2. By applying the EU standard as an upper limit, they estimated 2.60 million premature deaths in total; 17 % less than their base estimate for 2010 (Giannadaki et al., 2016).

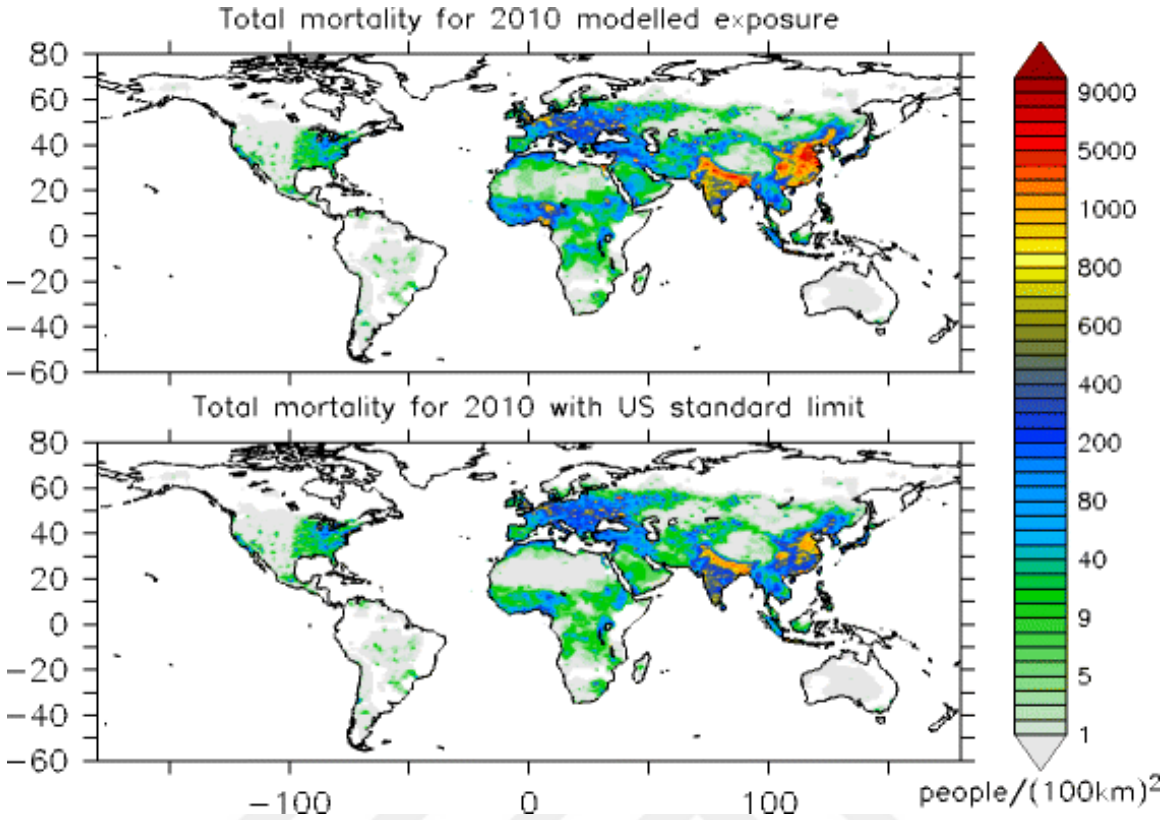

Figure 14. $PM_{2.5}$ related premature mortality around the world in 2010 and after implementing the United States standard of 12 µg/m³.
Source: http://media.springernature.com/full/springer-static/image/art%3A10.1186%2Fs12940-016-0170-8/MediaObjects/12940_2016_170_Fig2_HTML.gif

By applying the United States standard as an upper limit, they calculated a 46% reduction of global premature mortality compared to the 2010 estimates, preventing about 1.44 million deaths. The annual mortality could be reduced from 52 to 49 thousand per year for the United States. If the relatively strict 12 µg/m^3 limit were applied in China, premature mortality could be reduced by 69%, and about 911 thousand premature deaths would be avoided per year. In India the implementation of the 12 µg/m^3 limit could reduce premature mortality by about 49% and about 281 thousand deaths would be avoided per year. Therefore, implementing the stricter the United States standard (relatively low concentration levels) could make a significant difference around the world especially for highly populated areas. Some countries which are overwhelmed by natural $PM_{2.5}$ sources such as desert dust have relatively smaller benefits. Countries near the dust belt could never have benefits by implementing this standard and meet the strict US limit, not even the EU limit, because the annual mean $PM_{2.5}$ concentrations caused by natural sources typically range above those limitations (Giannadaki et al., 2016).

Table 2. Top 20 countries with highest annual premature mortality attributed to $PM_{2.5}$ in 2010 without and with implementing the EU and the United States $PM_{2.5}$ standards.

Country	Year 2010 deaths ($\times 10^3$)	EU limit (25 μg/m^3) deaths ($\times 10^3$)	US limit (12 μg/m^3) deaths ($\times 10^3$)
China	1,327	910	416
India	575	502	294
Pakistan$^{\alpha}$	105	84	67
Nigeria$^{\alpha}$	89	78	76
Bangladesh	85	76	38
Russia	67	67	66
USA	52	52	49
Indonesia	51	48	33
Ukraine	51	51	49
Vietnam	43	36	18
Germany	34	34	26
Egypt$^{\alpha}$	34	33	33
Turkey	31	31	25
Iran$^{\alpha}$	25	24	22
Sudan$^{\alpha}$	24	24	24
Japan	24	24	21
Myanmar	21	21	14
Italy	19	19	15
Iraq$^{\alpha}$	19	19	19
Thailand	18	18	15
World	3,155	2,600	1,712

α → $PM_{2.5}$ is dominated by desert dust in these countries.

2. PARTICULATE MATTER MEASUREMENT METHODS

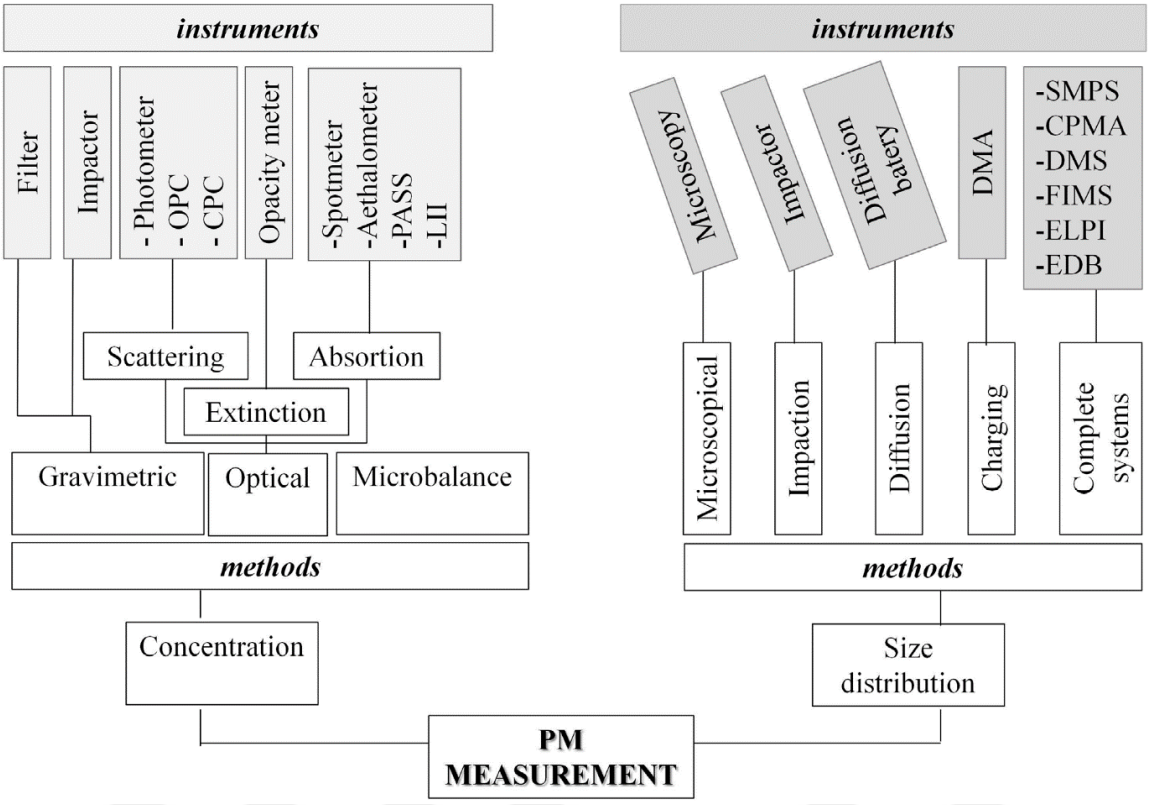

Figure 15. Methods and instruments for PM measurement.
Source: http://www.mdpi.com/2073-4433/6/9/1327

Measurements of particles can vary widely. This variation is mainly caused by the equipment used for measuring particles and the sampling procedures. There are several instruments for measuring characteristics of particulate matter. The most common particle measuring instruments are classified as concentration methods and size distribution methods. Instruments that measure particle concentration are used to standardize emission limits and check the standards of ambient air quality. Instruments that measure particle size distribution use the behavior of particles such as diffusion, aerodynamics, and optical and electrical mobility and they are used to understand the behavior of particles in the ambient air (Amaral et al., 2015). The main instruments and methods of measuring concentration (gravimetric, optical, and microbalance) and size distribution (microscopical, impaction, diffusion, charging, and complete systems) are shown in Figure 15.

There is not a perfect instrument for measuring particulate matter, but there is an appropriate instrument for each situation and study objective. When choosing an instrument for particle measurement, researchers should consider the ability to sample particles in real-time, dilution needs before sampling, the detection limit of the equipment, desired size range of the instrument, accuracy of the equipment, and durability and maintenance requirements.

2.1. SIZE DISTRIBUTION MEASUREMENT METHODS

The microscopical method involves the analysis of particle size via a collection of particles directly from filters followed by filter preparation to improve visibility in a microscope. Besides providing information on the dimensions of solid particles, electronic microscopy also provides a broad range of information about morphology, radius, the size distribution of aggregates, fractal dimension, number of primary particles per aggregate, and size distribution of primary particles (Amaral et al., 2015).

The working principle of impaction method is gravimetry with multiple impact stages. The most commonly used impactors are the cascade type, which operate based on the inertial classification of particles. In this type of measurement, the sample passes through a sequence of stages. In each stage, an air jet containing the aerosol reaches the impacting plate and particles larger than the cutoff diameter for the stage are collected. Smaller particles follow the gas flow that surrounds the collection plate and are collected in the next stage. This process continues until the smallest particles are removed in the after-filter (Amaral et al., 2015). The most used impactors are Andersen Impactors, Dekati Low-Pressure Impactors (DLPI), Berner Low-Pressure Impactors (BLPI), Micro-Orifice Uniform Deposit Impactors (MOUDI), and Electrical Low-Pressure Impactors (ELPI).

In the diffusion method, the size distribution of small particles is determined by separating particles based on their mobility. In contrast with larger particles, smaller particles (< 0.1 μm) are not strongly influenced by gravitational and inertial forces. Therefore, their behavior is not well represented by aerodynamic diameter because particle movement is generally dominated by diffusion. In this case, the diffusion method becomes

more appropriate for nanometric particles (Amaral et al., 2015). Diffusion Batteries were developed to determine the diffusion coefficients particles. Diffusion Batteries like the Electrical Diffusion Batteries (EDB) are frequently used instruments in the diffusion method.

In the charging method, the working principle is separation based on electrostatic charge. The particles are loaded with well-defined charge distributions. After loading, particles are inserted into an electrostatic classifier that allows particle passage in a narrow range of electric mobility. Classified particles are measured by an electrometer (Amaral et al., 2015). The most common instruments are Differential Mobility Analyzers (DMA) and Volatility Tandem Differential Mobility Analyzers (VTDMA).

Scanning Mobility Particle Sizers (SMPS) measure the particle mobility diameter, Centrifugal Particle Mass Analyzers (CPMA) classify particles based on the mass-to-charge ratio, Differential Mobility Spectrometers (DMS) measure the mobility size distribution of the mass-classified particles in real-time, Fast Integrated Mobility Spectrometers (FIMS) provide information about particle concentration and the particle mobility diameter, Electrical Low-Pressure Impactors (ELPI) classify particles according to their aerodynamic diameter, in addition to measuring the concentration and particle distribution in number, Electrical Diffusion Batteries (EDB) measure particles sizes using differences in their mobility level.

2.2. CONCENTRATION MEASUREMENT METHODS

In the gravimetric method, the particle mass concentration is determined by weighing the filters before and after the sampling period. Particle sampling using filters needs a specific sampling time of 15 min or more, therefore the identification of fast processes is not possible, but particles collected in the filter can be analyzed chemically. Determination of PM mass can be altered, depending on the collecting conditions of the filter. Filters must be packed and stored under controlled conditions of temperature and relative humidity for accurate measurement (Amaral et al., 2015). Cascade impactors are frequently used instruments that utilize the gravimetric method.

In the microbalance method, the particle mass concentration is determined by collecting the particles over the surface of an oscillatory microbalance element. When they are collected, those microbalances use alteration of the resonance frequency to determine the particle mass (Amaral et al., 2015). Tapered Element Oscillation Microbalances (TEOM) and Quartz Crystal Microbalances (QCM) are the two main measurement instruments that use the microbalance method.

In the optical detection methods, the particle mass concentration is determined using a light beam and a detector. Optical instruments used for measuring particle concentration in real time and can be based on the principles of scattering, absorption, or light extinction (Amaral et al., 2015).

2.2.1. Light Scattering

The effect that is produced when a light beam hits a small object (a particle or a molecule) and changes direction is called light scattering (Øgendal L., 2016). Light scattering technology is based on this simple principle and is used to measure the concentration of particulate matters by employing some other specific equipment. Airflow is drawn through a chamber for measurement by employing a fan or pump. After arriving at the optical sensor zone, an infrared light source illuminates a sample of particles at a given angle and a photodetector measures the scattered light. The measured light is scattered from a combination of all particles present in the optical detection zone, in one or more angles. Most commercial light scattering instruments use visible light (~600 nm) and measuring angles of 90°, 45°, or less than 30°. Many instruments also have the ability to register data like concentration measurements, particle size, and other environmental information like temperature and relative humidity (Amaral et al., 2015; Kelly et al., 2017). A schematic view of the light scattering principle is shown in Figure 16.

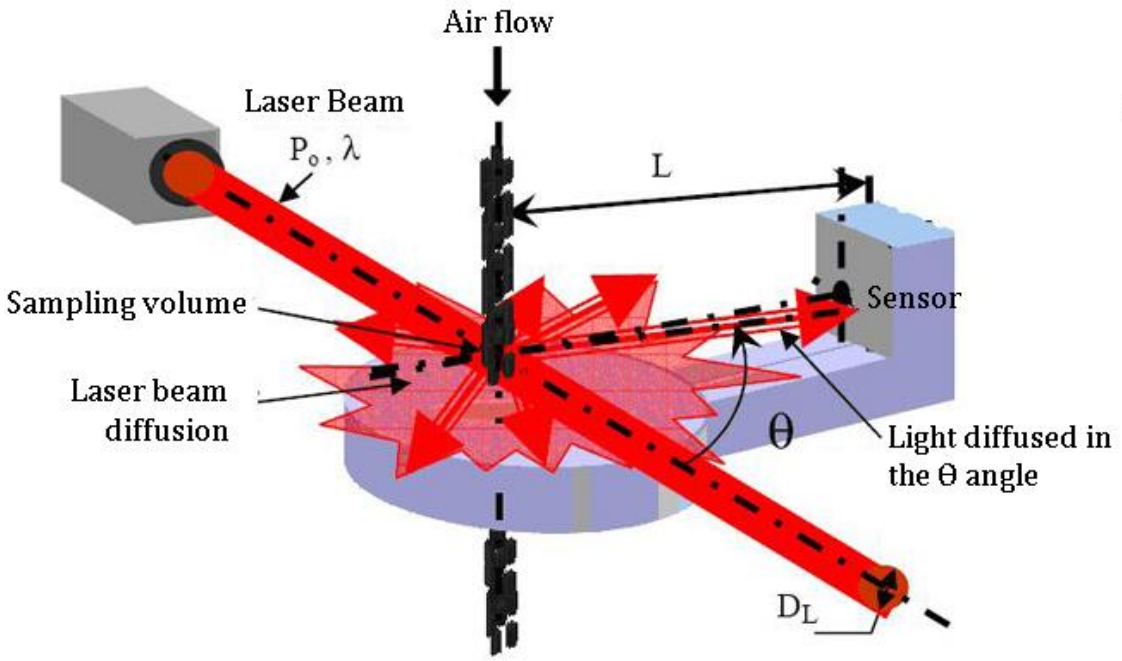

Figure 16. A schematic view of the light scattering principle.
Source: https://www.nano-sense.com/en/P4000/p4000-fine-particles-probe.html

2.3. REFERENCE, EQUIVALENT, AND REGIONAL METHODS

There are six criteria air pollutants regulated by National Ambient Air Quality Standards (NAAQS), these criteria pollutants include: sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), particulate matter (PM_{10} and $PM_{2.5}$), ozone (O_3), and lead (Pb). NAAQS focuses on protection of human health, protecting ecosystems and property/built environment. Compliance of the standards and monitoring is primarily carried out by state, local, and tribal governmental air pollution control agencies across the United States. The US Environmental Protection Agency (EPA) has developed a systematic framework of: (a) field measurements of ambient air pollutant levels using samplers, monitors, analyzers, and measurement devices (both filter-based and non-filter-based); (b) protocols and methodologies for laboratory analyses of criteria air pollutants; (c) standard operating procedures for samplers, monitors, analyzers, and measurement devices; (d) procedures for testing and analysis of monitoring systems and implementing laboratory analyses; (e) quality assurance/quality control procedures governing field measurements, laboratory analyses, operations, and testing; and (f) research, development, analysis, and

assessment of field measurement systems and laboratory analysis protocols. Enforcement of environmental laws and regulations can't be accomplished without monitoring of pollutants to determine where, when, and if violations are occurring. Monitoring ambient air quality to determine compliance with NAAQS requires the use of either Federal Reference Methods (FRMs), Federal Equivalent Methods (FEMs), or Approved Regional Methods (ARMs) (Hall et al., 2012). A schematic comparison between FRMs/FEMs/ARMs is shown in Figure 17.

	FRM	FEM Class II	FEM Class III	ARM
Defined as	Method defined by Appendix L to Part 50 for PM2.5 or Appendix O for PM10-2.5	Samples collected by filtration, with filter conditioning, and gravimetric analysis, but having substantial design differences from FRM	Having one-hour or less concentrations as well as 24-hour	Continuous $PM_{2.5}$ method approved within a State or local air monitoring network
Design or performance based	Design	Performance	Performance	Performance
Filter/ Continuous	Filter-based	Filter-based	Continuous	Continuous
Time Resolution	24-hour	24-hour	Hourly	Hourly
Network Applicability	National	National	National	Individual Network
Applicable to	$PM_{2.5}$, $PM_{10-2.5}$	$PM_{2.5}$, $PM_{10-2.5}$	$PM_{2.5}$, $PM_{10-2.5}$	$PM_{2.5}$ only

Figure 17. A schematic comparison between FRMs/FEMs/ARMs.
Source: https://www3.epa.gov/ttn/amtic/files/2006conference/hanleypmcont.pdf

Federal Reference Methods (FRMs) have been developed and designated by the US EPA for specific criteria pollutants and have completed a rigorous testing and analysis protocol. Successful completion of this process and designation as a 'reference method' means that the instrument can be used to monitor compliance for the appropriate primary and/or secondary NAAQS standards for any specific criteria pollutants (Hall et al., 2014). $PM_{2.5}$ measurement with FRMs is a 24-hour average manual filter-based method that includes filter weighing in the laboratory. Moreover, they specify the physical sampler, the operating conditions of the sampler, the required filter substrate required filter weighing conditions for mass determination, quality assurance and quality control (QAQC) requirements (Schauer, 2015).

Federal Equivalent Methods (FEMs) have been developed and designated by the US EPA as alternative specific criteria pollutants measurement methods. Air pollution measurement devices incorporating recent technologies are tested and evaluated through the equivalent method process before use in the US air monitoring network (Hall et al., 2014). There are three different FEMs for $PM_{2.5}$ measurement which are summarized as Class I, Class II, and Class III. Class I is nearly the same and there are minor changes compared to the FRMs. Class II includes all other manual filter-based methods that use 24-hour sampling and off-line filter weighing. Class III includes all methods that do not use manual filter-based methods for off-line filter weighing (Schauer, 2015).

Approved Regional Methods (ARMs) have been developed and designated by the US EPA as alternative measurement approaches for specific criteria pollutants. $PM_{2.5}$ mass measurement methods include continuous methods that can replace FRMs in specific regions (Hall et al., 2014). ARMs are continuous methods approved for use within a State, Local or Tribal agency and mainly use FEMs Class III certification. ARMs must meet the same QAQC requirements as the FRMs as well as the requirements from the Performance Audit System and co-locations of samplers. ARMs only can replace the use of FRMs at specific sites once their performance is demonstrated to be sufficiently equivalent to the FRMs in that region. ARMs are still being re-evaluated by EPA (Schauer, 2015).

2.4. FIXED MONITORING STATIONS vs LOW-COST SENSING

Monitoring air pollutants and measuring their ambient concentration is important because regulatory decisions and policies by governmental agencies are made based on those data. As a worldwide application, ambient air pollution concentrations for various air pollutants are measured using instruments such as fixed monitoring stations (FMSs). Although these instruments are reliable, and the reliability of the measured data is ensured by applying standard procedures for calibration, data collection, and post-processing, these instruments are designed for research purposes (Kumar et al., 2015). In addition, they are generally not user-friendly and require experienced users to operate them due to their complexity. Moreover, they are expensive, and a significant amount of investment is required to maintain and regularly calibrate them. Often, small quantities of FMSs are used

at designated sampling points (Kumar et al., 2015) which leads limited spatial coverage in many places (Gao et al., 2015).

In many cases, these monitoring stations are placed in secured areas with lower human interaction. Additionally, it is preferred to locate FMSs away from roadsides, crowded city centers, industrial zones, and major traffic congestion areas where local ambient air quality is affected by various emissions from diverse sources. This distribution method/preference often fails to represent the localized air quality data, local air pollution trends, and the actual exposure levels of air pollutants (Kumar et al., 2011, Wang et al., 2011, Gao et al., 2015). The current networks fail to capture spatiotemporal variations of air pollutants (Gao et al., 2015) and as a result, $PM_{2.5}$ exposure may be significantly under-estimated (Meng et al., 2012). A study in New York showed that the real-time exposure to $PM_{2.5}$ can be between 20–200% higher than the readings from local FMSs (Wang et al., 2011). Similar studies that examined personal exposure in different transportation microenvironments found that individuals may be exposed to much higher ambient $PM_{2.5}$ concentrations than local FMSs indicated (de Nazelle et al., 2012; Int Panis et al., 2010; Kaur et al., 2005; Kaur et al., 2007). Although modeling studies can be used to solve those problems, various quantities of data and inputs, computing facilities, experienced researchers, and longtime modeling runs are required.

A new and innovative method of measurement, low-cost monitors, may present a possible solution to the problems with FMSs. Technological improvement and continued development of low-cost sensing technology have made low-cost monitors less expensive, easier to deploy, operate, and manage than traditional systems. Low-cost monitors can be deployed in significant numbers for the same price as a single FMS. By doing so, it is easy to create monitoring networks for designated areas or even cities, calculate emission inventories of various pollutants, measure real-time short-term and long-term exposure of users in some designated areas, detect pollution hotspots and high concentration zones, and with the help of this more accurate data, focus on air pollution mitigation strategies (Steinle et al., 2013; Steinle et al., 2015; Gao et al., 2015). These monitors can be used by individuals or researchers to understand real personal exposure values in different microenvironments. Low-cost monitor networks especially help to provide a more detailed picture of indoor air quality and reliable data about indoor air quality levels, which is quite

important since people spend most of their time in indoor environments (Steinle et al., 2015). Some low-cost PM sensors have been evaluated for their performance in designated field and laboratory studies that found these PM sensors were promising for the future applications and useful as monitoring equipment both indoors and outdoors (Austin et al., 2015; Gao et al., 2015; Holstius et al., 2014; Kelly et al., 2017; Wang et al., 2015). Moreover, some projects exist that are dedicated to measuring ambient air concentrations of pollutants in the urban areas with low-cost monitors. Some such initiatives are the OpenSenseMap project (OpenSenseMap, 2017) which is mainly used by European users, OpenAQ (OpenAQ, 2017), and Purple Air platform (PurpleAir, 2017) which have active users both in Europe and in the United States. Air quality data collected from low-cost monitors that are connected to the internet is shared online for the users, public, and researchers. Some available commercial low-cost air quality sensors are shown in Figure 18.

Figure 18. Some of the low-cost air quality sensors on the market. from right to left: Air Quality Egg, Speck, Breeze, Laser Egg.
Sources: https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcS5GDvcO7Wovl9gEnVMzVNbLiDUbd4PqX8ywflz1ST6jXZ9V7NW
https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcRQo6TJqNB4N1VnWyjgIcbE3aenUHsgBDO3tI9BpnhExQn_YMcY
https://solarimpulse.com/files/offers/image_1/2017-11-21-105401/small_Breeze-Low-Cost-Air-Quality-Sensors.png
https://www.thebeijinger.com/sites/default/files/thebeijinger/blog-images/462/origins_detector_board_1.jpg

3. PERFORMANCE EVALUATION OF LOW-COST SENSORS

An interesting study took place in Beijing, China in 2016. They used two low-cost particulate matter sensors (Plantower PMS 3003) for ambient $PM_{2.5}$ measurement. According to project plan, two of the sensors placed on the rooftop of one of the buildings in Peking University (PKU) for 2.5-week period and the performance of the low-cost sensors was compared against a tapered element oscillating microbalance (TEOM) on a nearby rooftop on the Peking University's campus (Johnson et al., 2018).

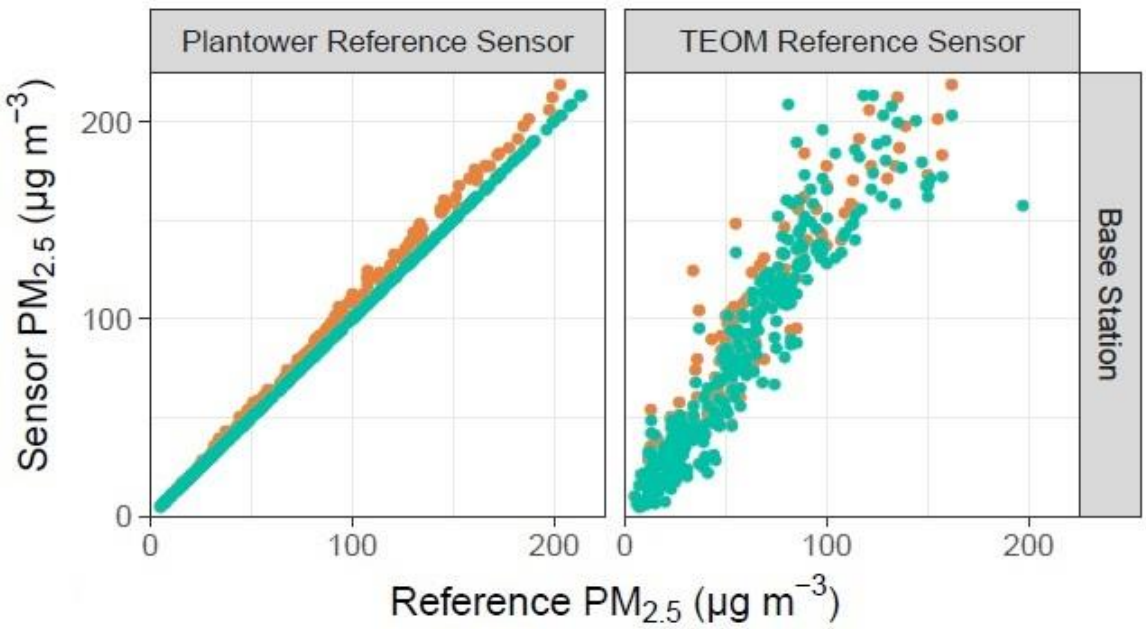

Figure 19. Comparison of 2 low-cost sensors data against a TEOM when collocated at rooftops on Peking University's campus.
Source: Johnson, K.K., Bergin, M.H., Norris, C., Schauer, J.J., Zhang, Y., Zhang, J., 2018. Low-cost methods for quantifying the effects of indoor air filtration on indoor air quality and personal exposure in Beijing, China. (Under Review)

Figure 19 illustrates the 1-hour averaged data for both low-cost sensors and the TEOM located on the PKU roof. It shows the comparison of the two low-cost sensors that were placed on the top of the building. Since one of the low-cost sensors was used as a reference the line between the sensor and itself (in green) is a perfect fit while the other sensor (in orange) has a slope slightly greater than one (m = 1.07) and an R^2 of 1. These sensors and the TEOM had an R^2 of 0.96 at a 1-hour average over this 2.5-week period (Johnson et al., 2018).

A previous study focused on comparing 1-hour averaged data from an earlier version of the Plantower sensor (PMS 1003) with a TEOM under ambient $PM_{2.5}$ concentrations in Utah, Arizona (0-80 µg/m^3). They showed lower correlations with TEOM (R^2= 0.5-0.8) than Johnson's study due to the relatively lower concentration range experienced in there (Kelly et al., 2017; Johnson et al., 2018). Higher R^2 values are likely due to the larger concentration range experienced in Beijing (0-225 µg/m^3) for their study (Johnson et al., 2018).

The high correlation between low-cost sensors and the TEOM shows that the sensors are well suited to capture ambient $PM_{2.5}$ concentrations in Beijing during this study. Their performance was high, and their measurements were highly correlated with TEOM which make them a reliable instrument to use for ambient $PM_{2.5}$ measurements, especially with the environments with a prominent level of $PM_{2.5}$ concentrations.

4. LOW-COST $PM_{2.5}$ MONITORS STUDY IN MUSCAT, OMAN

This study's main approach framework focused on deploying 10 low-cost monitors in different areas of Muscat, including both in indoor and outdoor microenvironments. The study lasted around three months to look at spatial gradients of $PM_{2.5}$ concentrations. The research study began in July 2017 and it ended in October 2017. It is the first air pollution/quality study in Muscat, OMAN utilizing low-cost monitors to study the spatial distribution of $PM_{2.5}$ concentrations. Moreover, low-cost monitors were collocated and run in the same place/microenvironment at the beginning and the end of the study to see their corresponding to each other. By doing so, we wanted to see if they were still valid and working properly after exposing the same $PM_{2.5}$ concentrations. In this study, we believe that having various $PM_{2.5}$ concentration datasets will help us to understand the ambient pollution levels and personal exposure to $PM_{2.5}$ related air pollution in Muscat, OMAN.

4.1. MATERIALS AND METHODOLOGY

4.1.1. Study Area

Muscat is the capital and largest metropolitan city of the Sultanate of Oman and had a population of 1.28 million in September 2015 (NCSI, 2018). Muscat has been known since the early 1st century as an important trading port between the west and the east and has been ruled by various indigenous tribes as well as foreign powers such as the Persians, the Portuguese Empire and the Ottoman Empire at various points in its history. Since the ascension of Qaboos bin Said Al-Said as Sultan of Oman in 1970, Muscat has experienced rapid infrastructural development. His extensive modernization program has opened the country to the outside world and has led to the growth of a vibrant economy and multi-ethnic society. Its economy is dominated by crude oil production and refining, natural and liquefied natural gas production, trading, porting, and other industrial activities (CIA, 2018). Moreover, due to rapid industrialization in the last few decades and adapting private transportation as a primary mode of travel and mobility, Muscat was ranked the 433rd the most polluted city by $PM_{2.5}$ concentration in the WHO's Global Urban Ambient Air Pollution Database. According to WHO, Oman's annual mean $PM_{2.5}$ concentration was

48.2 µg/m^3 in 2014 (WHO, 2018). The distribution of low-cost monitors in Muscat, OMAN is shown in Figure 20.

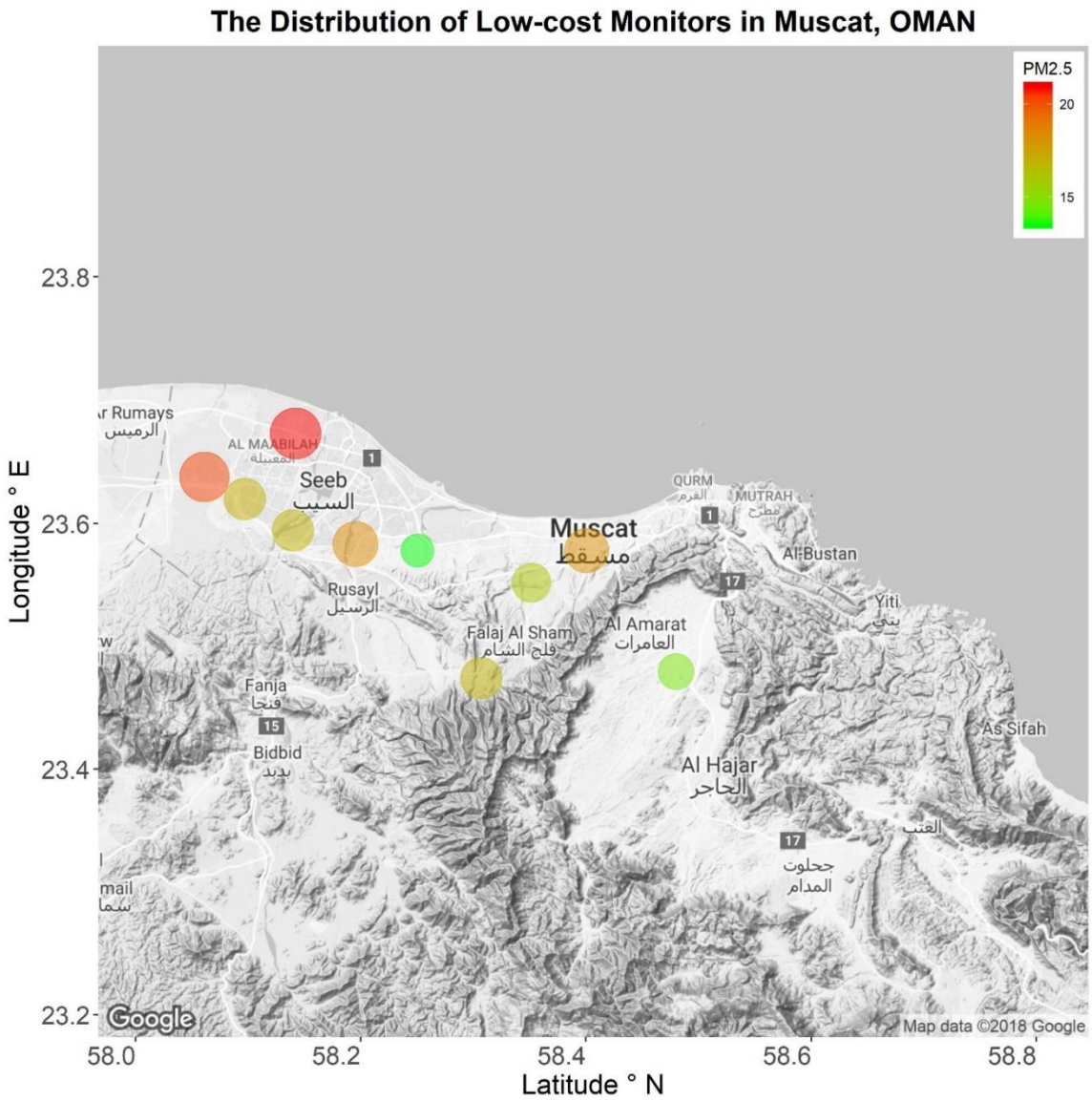

Figure 20. The distribution of Low-cost monitors in Muscat, OMAN and their 1-hour mean $PM_{2.5}$ concentrations.

4.1.2. Research Equipment

During the study period, 10 designed low-cost monitors were used. Each monitor had a $PM_{2.5}$ sensor, the teensy microcontroller, a clock, a humidity sensor, and a temperature sensor. Additionally, the device included protection case, voltage regulator, barrel jack power cable, LED indicator, micro-SD card, and battery. A Plantower $PM_{2.5}$

sensor (model: PMS 3003) costs $30; supporting circuitry, the enclosures, power cords, plug in, and external battery cost roughly an additional $170. The total cost of a package is around $200.

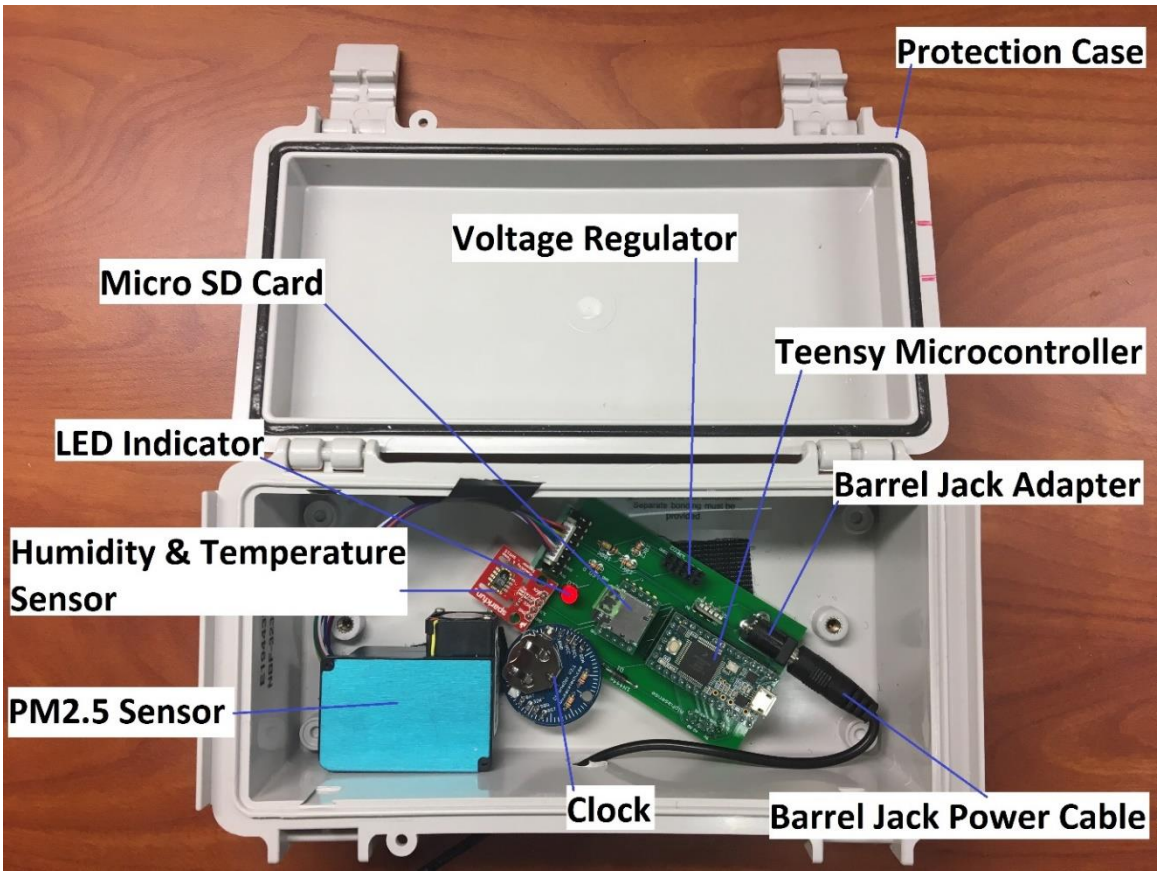

Figure 21. Description of the designed low-cost monitor.

The research equipment is user-friendly and easy to operate. There is no on/off button or screen which makes things simpler for users. When it is plugged into the energy source, the LED light indicator starts blinks and then continues to blink until it is unplugged from the energy source. It weighs 0.45 kg without the battery and its dimensions are 20x11x7.5 cm. The designed low-cost monitor and its parts are shown in Figure 21.

Each monitor can run approximately 55 hours with supplied Anker PowerCore 10400mAh battery, but this running time is slightly affected by environmental conditions such as temperature. During the study period as a general approach, wall-power was used and batteries were kept on standby. Additionally, an 8 GB micro-SD card was used. A large

data storage capacity was needed during the study period so that there was no concern about data storage or management.

4.1.3. Data Collection, Management, and Processing

The study continued for around three months, once the data was moved from the micro-SD card to the computer as a .txt file, the unnecessary data was deleted and then the cleaned data was converted into a .cvs file, the unnecessary data including startup information of the monitor for each start was deleted and then the cleaned data was converted into a .cvs file. After inputting, processing, and checking the data carefully, the final datasets were finally prepared. A spreadsheet application Microsoft Excel, a programming language for statistical computing and graphics RStudio, a simple raster graphics editor Microsoft Paint, a virtual globe program Google Earth and a general-purpose diagramming program yEd were used to create $PM_{2.5}$ related figures and tables for this study.

4.1.4. Data Validation

At the beginning and the end of the study, all the low-cost monitors were collocated, and run in the same place/microenvironment to be sure they were still valid and working properly. After being exposed the same $PM_{2.5}$ concentrations, data validity was assessed via showing similar correlations. 1-hour $PM_{2.5}$ concentrations from all measurements are summarized in Figure 22. During the 6 days of collocating study, they followed the same concentration change pattern even though there are small fluctuations of $PM_{2.5}$ concentrations between low-cost monitors which are shown in Figure 22.

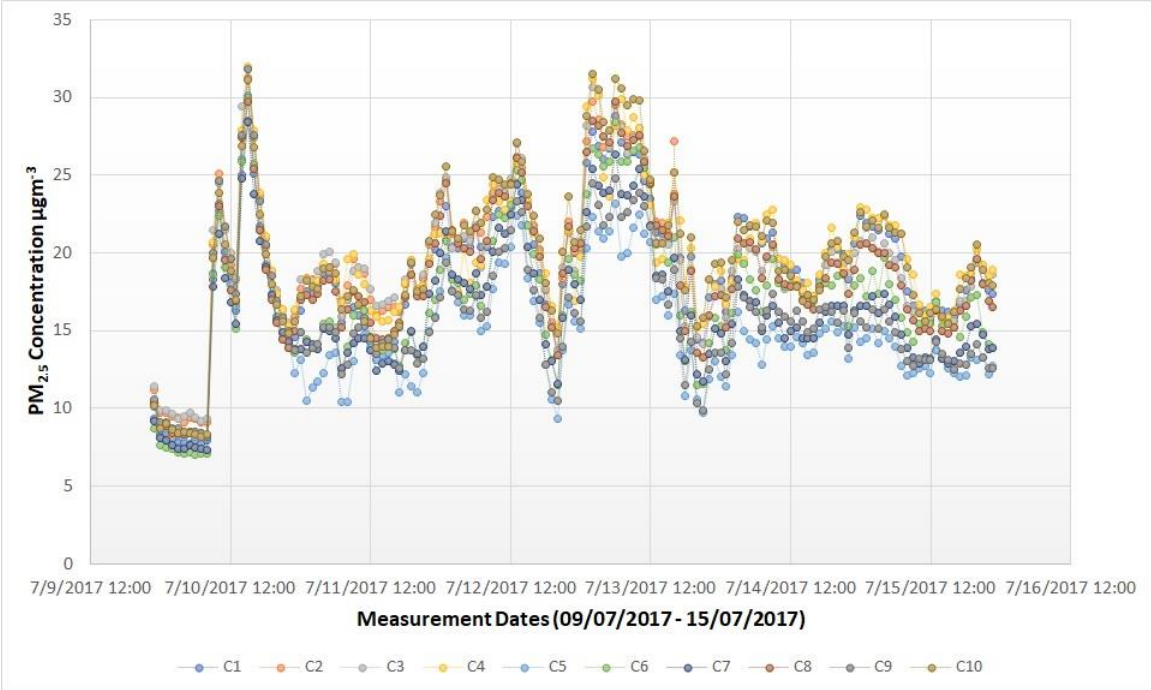

Figure 22. $PM_{2.5}$ concentration in the controlled environment at the beginning of the project.

1-hour averaged $PM_{2.5}$ concentration pairwise correlations between low-cost monitors at the first collocated site is shown in Figure 23. The pairwise correlations among the low-cost monitors are high and R^2 values are between 0.84 and 0.99. The minimum pairwise correlation is between C 1 and C 5 with a value of 0.84 and the maximum pairwise correlation is between C 5 and C 9 with a value of 0.99.

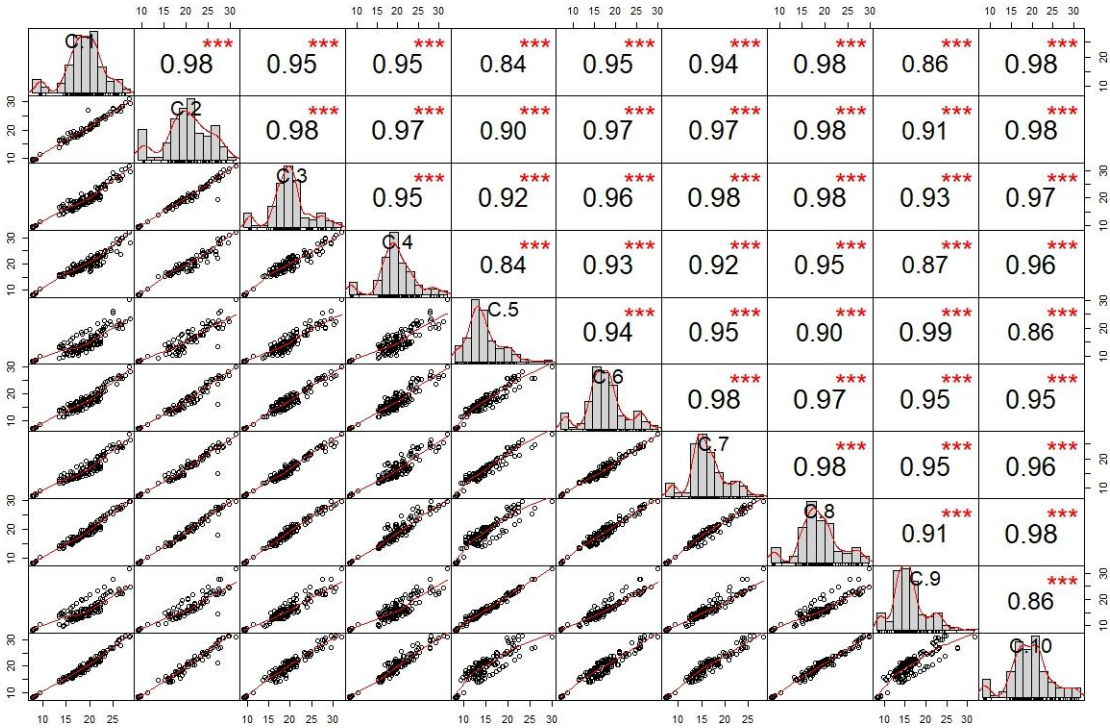

Figure 23. 1-hour averaged $PM_{2.5}$ concentration pairwise correlations between low-cost monitors at the collocated site from 9 July to 15 July 2017.

After the 3 months-long field study, the 4 days collocating study was done in another controlled environment. They still followed a similar concentration change pattern, again with some small fluctuations of $PM_{2.5}$ concentrations between low-cost monitors; this is shown in Figure 24. Two of the monitors, C 3 and C 7, were not functioning properly at the end of the study due to losing their micro-SD cards; thus, their collocated concentrations were not included in the second part of this low-cost monitor validating study.

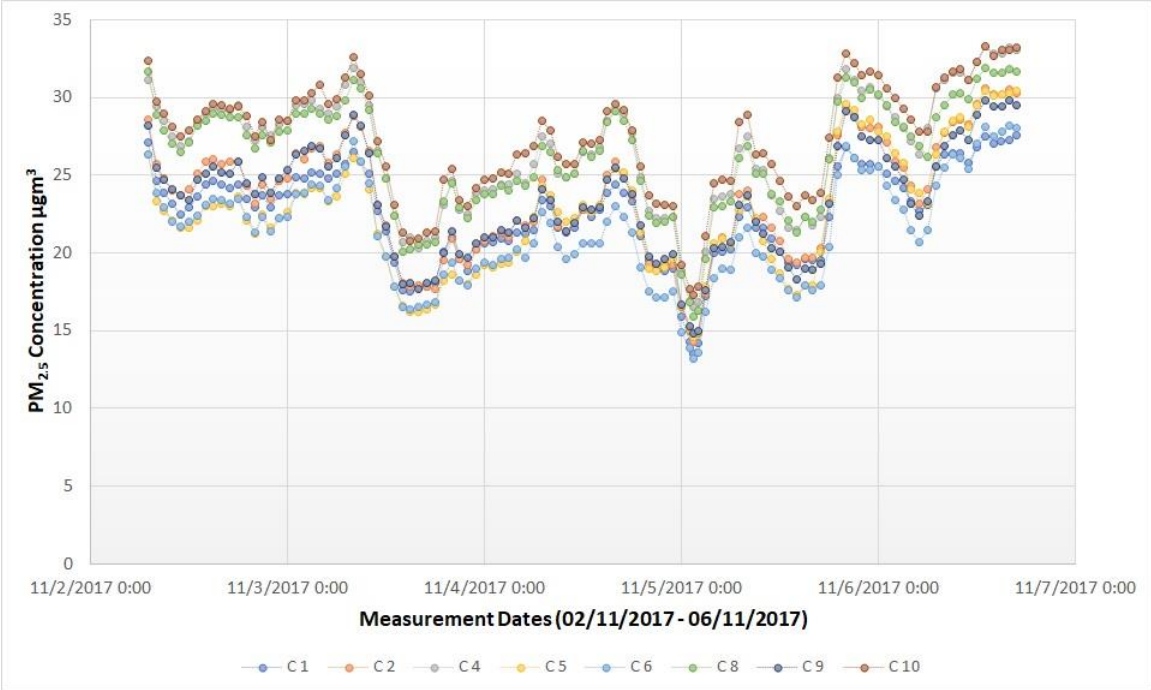

Figure 24. $PM_{2.5}$ concentration in the controlled environment at the end of the project.

We expected that the accuracy of the low-cost sensors might be affected by the long field study and high concentration of $PM_{2.5}$ exposure due to their well-known durability issues in extreme outdoor environmental conditions. Moreover, 1-hour averaged $PM_{2.5}$ concentration pairwise correlations between low-cost monitors at the second collocated site is shown in Figure 25. Surprisingly, the pairwise correlations among the low-cost monitors are higher than the pairwise correlation values at the beginning of the study. R^2 values are between 0.93 and 1.00 in this second collocating study. The smallest pairwise correlation is between C 5 and C 8 with a value of 0.93 and the largest pairwise correlation is between C 1 and C 8 and C 1 and C 10 with a value of 1.00. This high correlation may be resulted via having a 2 days short run in the controlled environment or not adding two datasets from two low-cost monitors (from C 3 and C 7) for the pairwise correlation calculations due to losing their micro-SD cards.

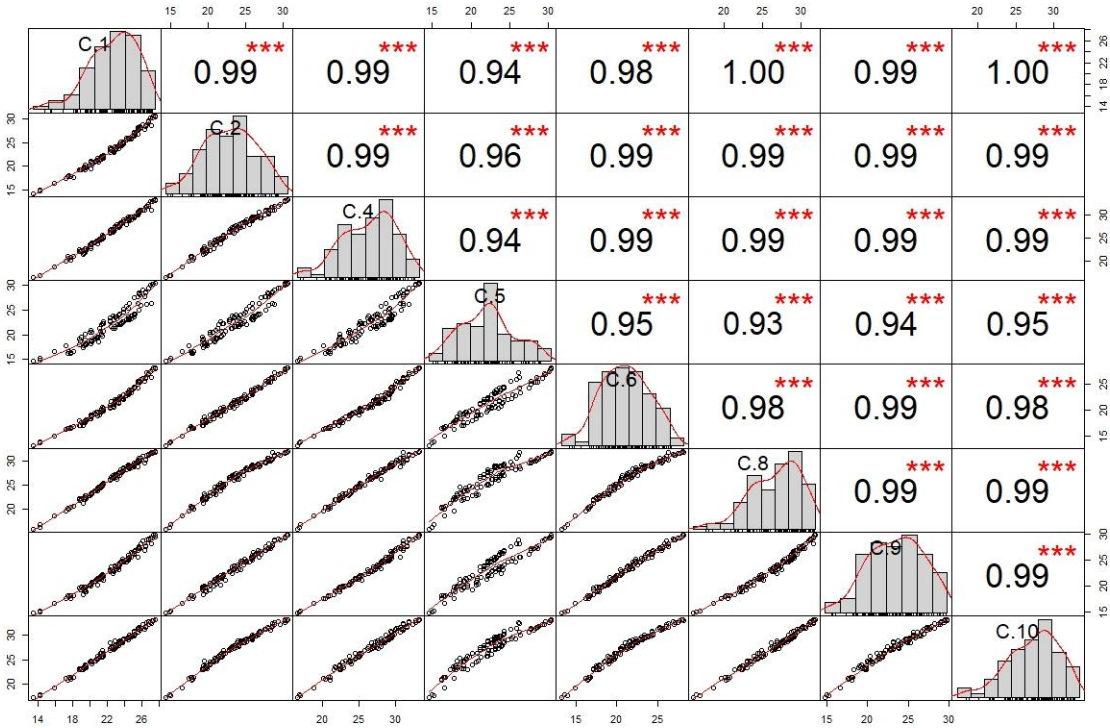

Figure 25. 1-hour averaged $PM_{2.5}$ concentration pairwise correlations between low-cost monitors at the collocated site from 2 November to 6 November 2017.

4.2. RESULTS

Figure 26 shows the total measurements from all low-cost monitors of $PM_{2.5}$ concentrations across the whole study. 1-hour average $PM_{2.5}$ concentration values from all low-cost monitors were used for graphing. The highest 1-hour average $PM_{2.5}$ concentration was 128.8 µg/m³ from C 10, the second one was 118.1 µg/m³ from C 2, and the third was 74.5 µg/m³ from C 9. There are 15,398 1-hour average $PM_{2.5}$ concentration data points, 14 % of which exceeded WHO's suggested 24-hour mean $PM_{2.5}$ concentration limit which of 25 µg/m^3.

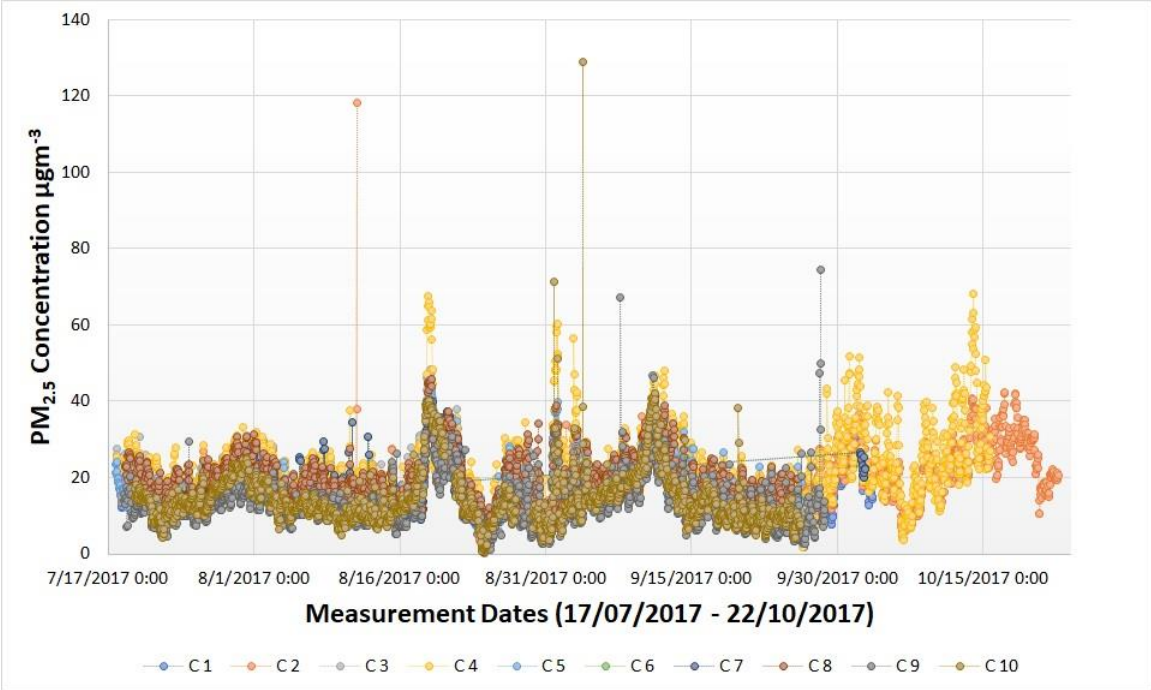

Figure 26. $PM_{2.5}$ concentrations from different monitors in Muscat, OMAN.

Table 3 summarizes annual mean $PM_{2.5}$ concentrations in Oman from various data sources including The Organization for Economic Co-operation and Development (OECD), the World Health Organization (WHO), The World Bank, State of Global Air, and Muscat study result. As can be seen in the table, the 1-hour mean $PM_{2.5}$ concentrations from the study are lower than the countries' yearly statistics from the given sources. The probable causes of this finding are meteorological factors such as temperature, humidity, precipitation, wind speed, and wind direction. This also may be related to the low performance of the monitors during those specific times of the year as compared to FMSs.

Table 3. 1-year mean $PM_{2.5}$ concentrations from various data sources and Southeast Asia study for the traveled countries.

	$PM_{2.5}$ Data Source ($\mu g/m^3$)				
Country	**OECD $^{\alpha}$**	**WHO $^{\beta}$**	**The World Bank $^{\gamma}$**	**State of Global Air $^{\delta}$**	**Muscat Study $^{\varepsilon}$**
Oman	64.7	48.2	53	53	17.4

α → OECD's 1-year mean $PM_{2.5}$ concentration data belongs to the year of 2015.
β → WHO's 1-year mean $PM_{2.5}$ concentration data belongs to the year of 2014.
γ → The World Bank's 1-year mean $PM_{2.5}$ concentration data belongs to the year of 2015.
δ → State of Global Air's 1-year mean $PM_{2.5}$ concentration data belongs to the year of 2015.
ε → 1-hour mean $PM_{2.5}$ measurements from Muscat, Oman study.

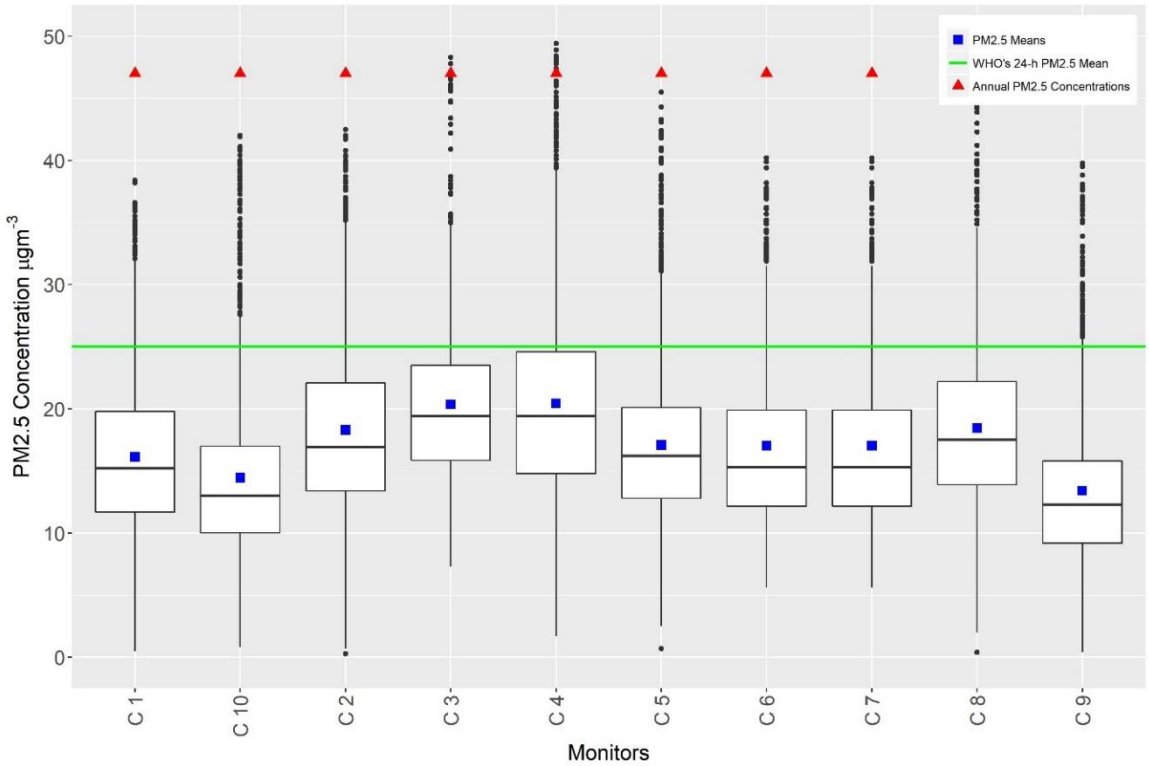

Figure 27. $PM_{2.5}$ concentrations from different monitors in Muscat, OMAN.

Figure 27 shows WHO's suggested 24-hour mean $PM_{2.5}$ exposure limit as a green line at 25 µg/m^3, WHO's annual mean $PM_{2.5}$ concentrations for Oman as a red triangle, and the Muscat study's 1-hour mean $PM_{2.5}$ concentration from all of the monitors as a blue square. The 1-hour mean $PM_{2.5}$ concentrations for all the low-cost monitors ranged from 13.5 to 21.0 µg/m^3. The highest 1-hour mean $PM_{2.5}$ concentration was 21.0 µg/m^3 from C 4, the lowest 1-hour mean $PM_{2.5}$ concentration was 13.5 µg/m^3 from C 9. The average 1-hour mean $PM_{2.5}$ concentration was 17.4 µg/m^3. More detailed explanations of the results of this study will be given in another article/thesis.

Limitations of our study include the short study period (3 months), lacking a complete $PM_{2.5}$ concentration dataset for whole seasons, and lacking a reliable ambient $PM_{2.5}$ concentration dataset from a nearby FMS in Muscat. Deploying these low-cost monitors nearby FMSs would help us to see their real performance in the field, but due to the limitations in our study, we were unable to deploy them close to those areas.

Several aspects of this study can be addressed in future work including: encouraging researchers to conduct further studies related to low-cost sensing, extending measurements

to a longer time frame to allow observation of seasonal patterns, using more low-cost monitors to test their performance not only indoors but also in outdoor environments, increasing the study area to other countries and continents, and deploying to them close to FMSs to see their actual performance in the field compared to current accepted methods. The most valuable result from this study is the higher 1-hour average $PM_{2.5}$ concentration pairwise correlations between low-cost monitors from the collocation studies in Muscat. Those results showcase the acceptable performance of those low-cost monitors and explain to us that they are a reliable instrument to use in the further research.

5. LOW-COST $PM_{2.5}$ MONITOR STUDY IN SOUTHEAST ASIA

Many particulate matter exposure studies are done using sensors in local environments to address the exposure of selected study groups like pedestrians, city dwellers, commuters, car drivers, and cyclists in different transportation environments. Often, findings are different both between and within studies due to different urban settings, cities' vehicle fleet, regional traffic configuration and congestion level, local emission profiles, ambient pollutant concentrations, and meteorological conditions (de Nazelle et al., 2012; Int Panis et al., 2010; Kaur et al., 2005; Kaur et al., 2007; Kingham et al., 2013; Knibbs et al., 2010; Steinle et al., 2015; Strak et al., 2010; Thai et al., 2007; Wang et al., 2011). In contrast, this study's main framework focused on a single traveler, including his daily activity, and the total exposure of $PM_{2.5}$ in 3 main microenvironments and 17 sub-microenvironments. Travelers are an important group that tend to have high personal exposure levels not only to $PM_{2.5}$ but also other pollutants. They can be a concerned group of people because the aims of traveling including exploring new destinations, seeing unfamiliar places, discovering new cultures and traditions, meeting new people, and trying new foods and drinks in the relatively short amount of time, lead to prominent levels of body activity. High body activity results in a large increase in breathing frequency and tidal volume which influences their inhaled dose of air pollutants and increased deposition on the target's lung tissues (Int Panis et al., 2010; de Nazelle et al., 2012). It is well-explained in another study that higher concentrations of $PM_{2.5}$ don't negate the health benefits of physical activity, but they do decrease the advantages of increased physical activity (Tainio et al., 2016).

This study lasted around two months to look at $PM_{2.5}$ exposure of a traveler in different microenvironments and countries. The research study began in June 2017 and it ended in August 2017. It is the first air pollution/quality study in Southeast Asia utilizing low-cost monitors to study the spatial distribution of $PM_{2.5}$ concentrations in different microenvironments of individual traveler. In this research approach, we believe that understanding more about personal exposure to $PM_{2.5}$ related air pollution is not only important for global travelers but also the local populations.

5.1. MATERIALS AND METHODOLOGY

5.1.1. Study Area and Travel Plan

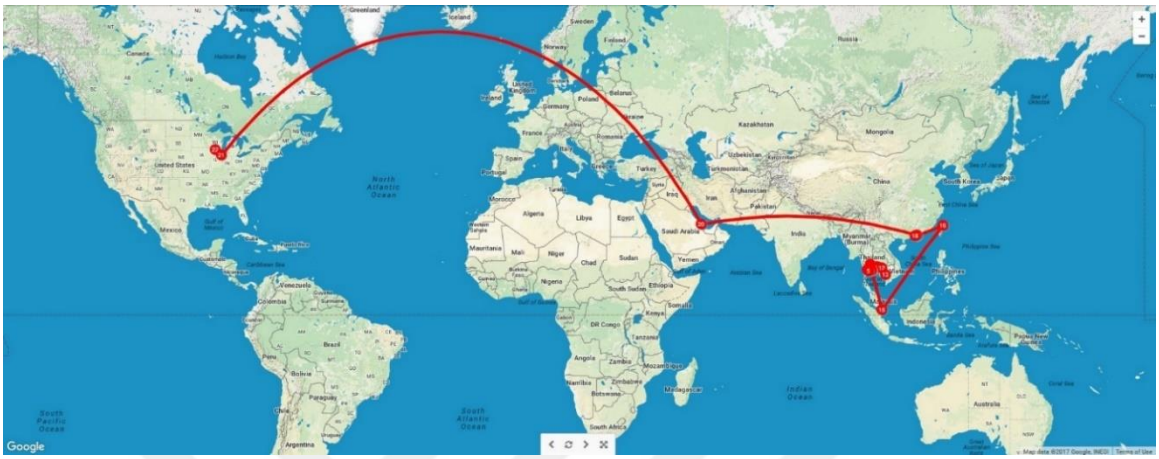

Figure 28. Summarized Southeast Asia travel plan on the world map.

During the study period, Thailand, Cambodia, Singapore, Taiwan, Hong Kong, Macau, Qatar, and the United States (17 cities: Bangkok, Ayutthaya, Phetchaburi, Hua Hin, Pattaya, Sattahip, Aranyaprathet, Poipet, Siem Reap, Phnom Penh, Singapore, Taipei, Hong Kong, Macau, Doha, Chicago, and Madison) were visited in 37 days. A summarized Southeast Asia travel plan is shown in Figure 28. There was no pre-designated travel plan or time distribution in the countries in order to mimic the unpredictable travel choices of a solo traveler. 18 days were spent in Thailand, 6 days in Cambodia, 3 days each in Singapore and Taiwan, 6 days in Hong Kong (nearly half of the day in Macau), and the rest of the activity data was recorded on the way back to Madison, WI, US through Doha, Qatar and Chicago, IL, US. The travel dates and times spent in each country, in addition to maximum, minimum and mean recorded $PM_{2.5}$ concentrations during those times are shown in Table 4. Not all recordings are well-represented for all the listed countries due to the limited travel and recording time in cities such as Doha, Qatar. It is believed that others such as Thailand, Cambodia, Singapore, Taiwan, Hong Kong were well represented because a relatively long amount of time was spent in the various microenvironments.

Table 4. Summary of time spent and measured 1-hour mean $PM_{2.5}$ concentrations in each country.

Dates	Time Spent	Country	Mean $PM_{2.5}$ in $\mu g/m^3$	Max $PM_{2.5}$ in $\mu g/m^3$	Min $PM_{2.5}$ in $\mu g/m^3$
24.06.2017 – 05.07.2017 11.07.2017 – 18.07.2017	416 hrs. 15 mins.	Thailand	9.6	525	0
05.07.2017 – 11.07.2017	132 hrs. 24 mins.	Cambodia	14.7	1,142	0
18.07.2017 – 21.07.2017	68 hrs. 3 mins.	Singapore	16.5	209	0
21.07.2017 – 24.07.2017	65 hrs. 28 mins.	Taiwan	10.9	161	0
24.07.2017 – 28.07.2017 28.07.2017 – 28.07.2017 28.07.2017 – 30.07.2017	134 hrs. 24 mins.	Hong Kong & Macau	16.0	162	0
30.07.2017 – 30.07.2017	2 hrs. 51 mins.	Qatar	12.4	18	0
30.07.2017 – 30.07.2017	9 hrs. 4 mins.	the United States	6.7	25	0

5.1.2. Microenvironments Approach

A microenvironment was described as a small space in which human contact with a pollutant takes place, and which could be treated as a well-characterized, relatively homogenous locations with respect to pollutant concentrations for a specified time in Ozkaynak's paper (Ozkaynak et al., 2008). Moreover, the microenvironments approach is commonly used in personal exposure and air quality studies to understand the effects of different variables on ambient $PM_{2.5}$ concentration. Indoor, outdoor and vehicle environments generally have different air pollution statistics and dynamics even though indoor and vehicle microenvironments are affected directly by outdoor microenvironments. In this study, 3 main-microenvironments and 17 sub-microenvironments were categorized and listed in Figure 29. This approach was utilized to this study to understand the effects of different microenvironments on personal exposure of $PM_{2.5}$ while traveling in different countries.

Figure 29. 3 main-microenvironments and 17 sub-microenvironments approach for this study.

During the study, the monitor was actively recording $PM_{2.5}$ concentrations for about 49,693 minutes (around 828.22 hours / 34.51 days). The non-recording time was about 2,991 minutes (around 49.85 hours / 2.08 days), due to file copying from a micro-SD card into the computer, changing the drained battery, closing the monitor because of the security checks at the airport, security concerns during international flights, and some other unforeseen issues. According to the activity log data, around 59% of the total recording time was spent indoors, 31% outdoors for travel activities, and 10% in vehicles for transportation purposes. Table 5 shows a more detailed picture of the total time spent in 17 sub-microenvironments. 32% and 27% of the total recorded time was spent in Hostel/Hotel/Spa category and House category, respectively. It was obvious that the main $PM_{2.5}$ exposure occurred in indoor environments; although some of the recorded logs are related to outdoor $PM_{2.5}$ concentration in the House category. This is consistent with a previous literature study with a similar result (Steinle et al., 2015). 11% and 7% of the total recorded time were related to high-level outdoor activities such as walking, hiking, and cycling in the Street and Attraction categories respectively. 6% of the total recorded time was also spent in both indoor and outdoor-based activities in Café/Pub/Restaurant category.

The total remaining recorded time was spent in other various microenvironment categories which are listed in Table 5.

Table 5. Summary of time spent and measured 1-hour mean $PM_{2.5}$ concentrations in each 17 sub-microenvironments.

Microenvironments	Recorded-Time (min.)	Percent Rate	1-hour Mean $PM_{2.5}$ in µg/m^3	$PM_{2.5}$ Exposure in µg-hour/m^3
HOSTEL/HOTEL/SPA	15,778	32	9.6	2,524.5
HOUSE	13,374	27	6.4	1,426.6
STREET	5,526	11	19.3	1,777.5
ATTRACTION	3,239	7	16.9	912.3
CAFÉ/PUB/RESTAURANT	2,938	6	29.6	1,449.4
PASSENGER CAR	1,695	3	2.3	65.0
BUS/TUKTUK/VAN	1,468	3	11.3	276.5
MARKET/SHOPPING MALL	1,300	3	19.3	418.2
AIRPORT/CUSTOM	1,176	2	13.8	270.5
CABLE CAR/METRO/TRAM	1,093	2	18.9	344.3
STATION	864	2	13.6	195.8
BOAT/FERRY	475	1	8.4	66.5
BEACH/SWIMMING POOL	379	1	10.6	67.0
PORT/STATION	361	1	32.8	197.4
PLANE	27	0	9.4	4.2
TOTAL	**49,693**	**100**		

5.1.3. The Study Participant/Traveler

The study participant/traveler was trained to use the monitor before beginning to travel. He had the related Health, Safety & Environment training and gained proper information how to use the designated research equipment during his traveling in Southeast Asia. He was also provided with a written operational manual. He was informed to choose his daily activity and trip plan randomly, but he was requested to record all microenvironment changes and their times into his smartphone. A set of a data which is related to the 3 main and 17 sub-microenvironments and the time series of the

microenvironmental change were gathered by using the notes from his smartphone. Temperature, humidity, 1-minute averaged $PM_{2.5}$ concentrations, and time information were gathered from the research equipment itself.

5.1.4. Research Equipment

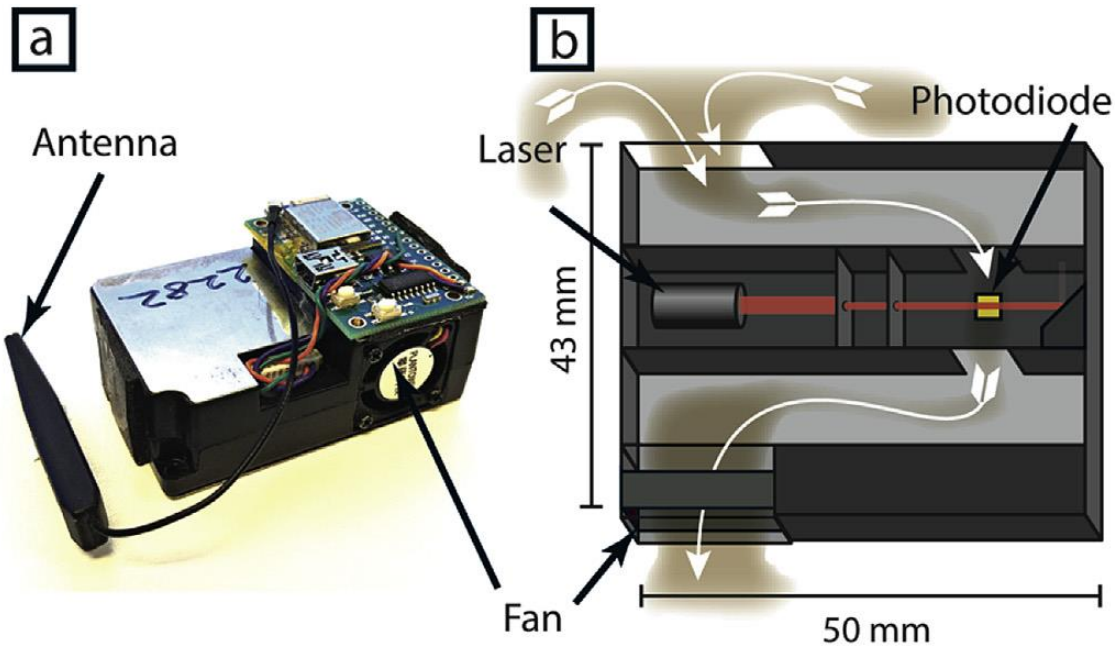

Figure 30. (a) Plantower PMS 3003 $PM_{2.5}$ sensor and (b) a schematic view of the Plantower PMS 3003 $PM_{2.5}$ sensor.

Source: https://ars.els-cdn.com/content/image/1-s2.0-S026974911632718X-gr1.jpg

During the study period, an assembled low-cost monitor was used. It had a Plantower PMS 3003 $PM_{2.5}$ sensor which was evaluated in controlled laboratory and ambient environmental conditions in a previous study and presented a reliable performance (Kelly et al., 2017). A schematic view of the Plantower PMS 3003 $PM_{2.5}$ sensor is shown in Figure 30. The Plantower PMS 3003 uses the light-scattering principle for particle counting. A fan is employed to draw air through a measurement chamber. 90° scattered light is detected by a photo-diode detector and the data is converted to a mass distribution ($\mu g/m^3$). The laser wavelength was estimated to be around 650 ± 10 nm. According to the manufacturer, it detects PM in the range of 0.3 µm to 10 µm, it has a 10-s response time

and its counting efficiencies are 50% @ 0.3 µg/m^3 and 98% @> 0.5 µg/m^3 (Kelly et al., 2017).

The teensy microcontroller, clock, humidity, and temperature sensors were the main parts of the research equipment. Other than these main system parts, some secondary parts included the protection case, voltage regulator, barrel jack power cable, LED indicator, micro-SD card, and battery. The research equipment is user-friendly and easy to operate. There is no on/off button or screen that can make things complicated for users. When it is plugged into the energy source, the LED light indicator starts blinks and then continues to blink until it is unplugged from the energy source. It weighs 0.3 kg without the battery and its dimensions are 15.5x8.5x4.5 cm which makes the instrument easy to carry. The assembled low-cost monitor and its parts are shown in Figure 31.

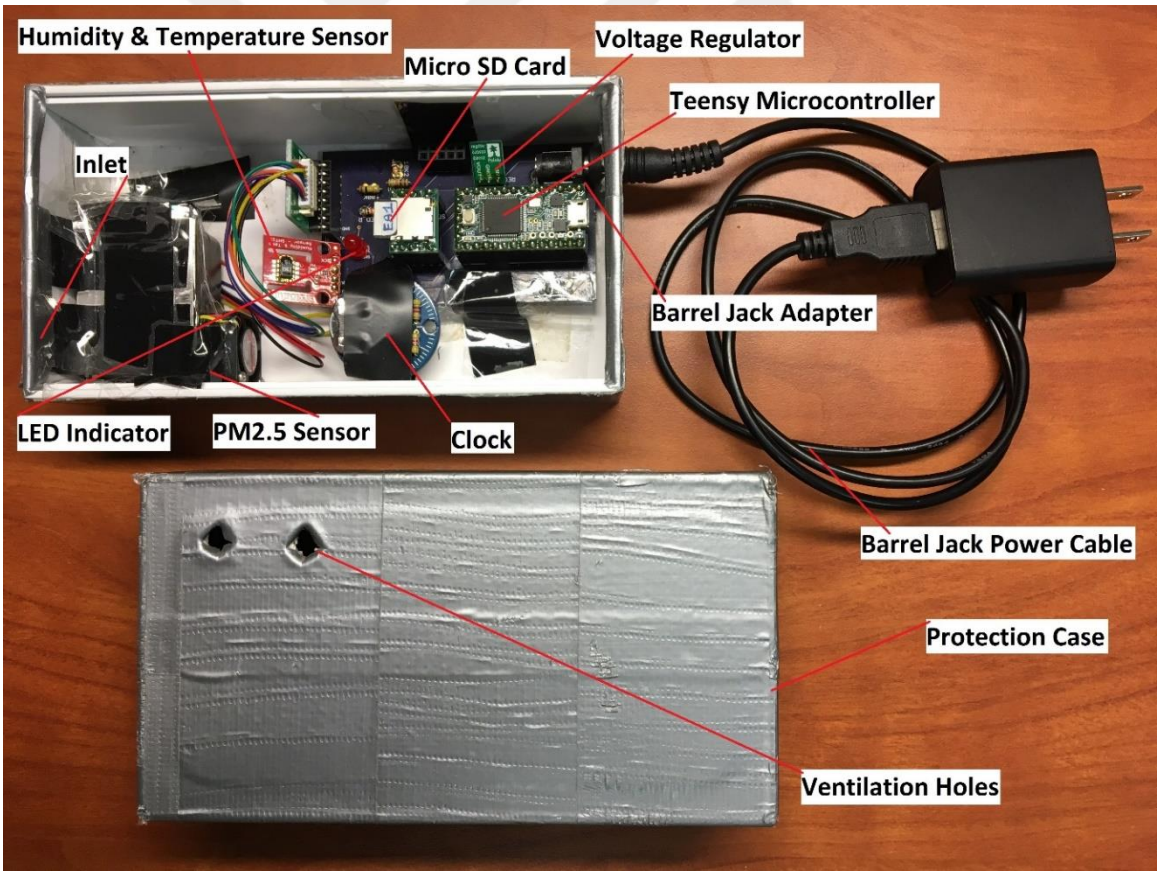

Figure 31. Description of the assembled low-cost monitor.

A 30 L hiking backpack with side pockets was used to carry the instrument with its inlet facing up for proper air uptake into the sensor's chamber. The backpack was generally

worn in the outdoor microenvironments and it was kept close to the bearer by placing it on a table, chair, seat, or the bearer's lap when it wasn't being worn in some of the vehicle and indoor microenvironments (Figure 32).

Figure 32. The backpack set up for the low-cost monitor.

The assembled low-cost monitor can run approximately 55 hours with used Anker PowerCore 10400mAh battery, but this running time is slightly affected by environmental conditions such as temperature. During the study period, two batteries were used. Either every day or two days in a row the used one was replaced with fully charged one. Moreover, an 8 GB micro-SD card was used. A large data storage capacity was needed during the study period so that there was no concern about data storage or management.

5.1.5. Data Collection, Management, and Processing

The data was collected for 37 days from June 24, 2017 to August 30, 2017 by using the assembled low-cost monitor. Once the data was moved from the micro-SD card to the computer as a .txt file, the unnecessary data including startup information of the monitor for each start was deleted and then the cleaned data was converted into a .cvs file to input microenvironments and countries data manually with using recorded notes data from the

smartphone. After inputting, processing, and checking the data carefully, the final datasets were prepared. A spreadsheet application Microsoft Excel, a programming language for statistical computing and graphics RStudio, a simple raster graphics editor Microsoft Paint, a virtual globe program Google Earth and a general-purpose diagramming program yEd were used to create $PM_{2.5}$ related figures and tables for this study.

5.2. RESULTS

Figure 33 gives brief information about the total measurements from the monitor for $PM_{2.5}$ exposures on selected days. All the concentration values that were used for graphing were 1-minute averaged $PM_{2.5}$ concentration. 3 days (June 25, 2017 - in Thailand, August 2, 2017 - in Thailand, and August 8, 2017 - in Cambodia) were selected to show prominent levels of $PM_{2.5}$ exposure while engaging in travel activities. The highest recorded concentration was 1,142 µg/m³ in an Outdoor – Café/Pub/Restaurant microenvironment while being exposed to tobacco smoke of the cigarette users around the pub. The second highest was 525 µg/m³ in an Indoor – Café/Pub/Restaurant microenvironment with exposure to hookah and tobacco smoke from the cigarette and hookah users in the café. This recorded value was lower than the first one even though they had a similar pollution source. The differences may have been related to distance from the pollution source, dilution effects of the air and wind, the position and placement of the monitor, and the average ambient concentration of $PM_{2.5}$ in those microenvironments. The third highest $PM_{2.5}$ concentration value was 492 µg/m³ in an Outdoor – Attraction microenvironment while being exposed to smoke from burning candles & incenses around the temple. As stated in Int Panis's and Gao's paper, the health effects of short bursts of high exposure to $PM_{2.5}$ in contrast to chronic exposure are not well understood (Int Panis et al., 2010; Gao et al., 2015).

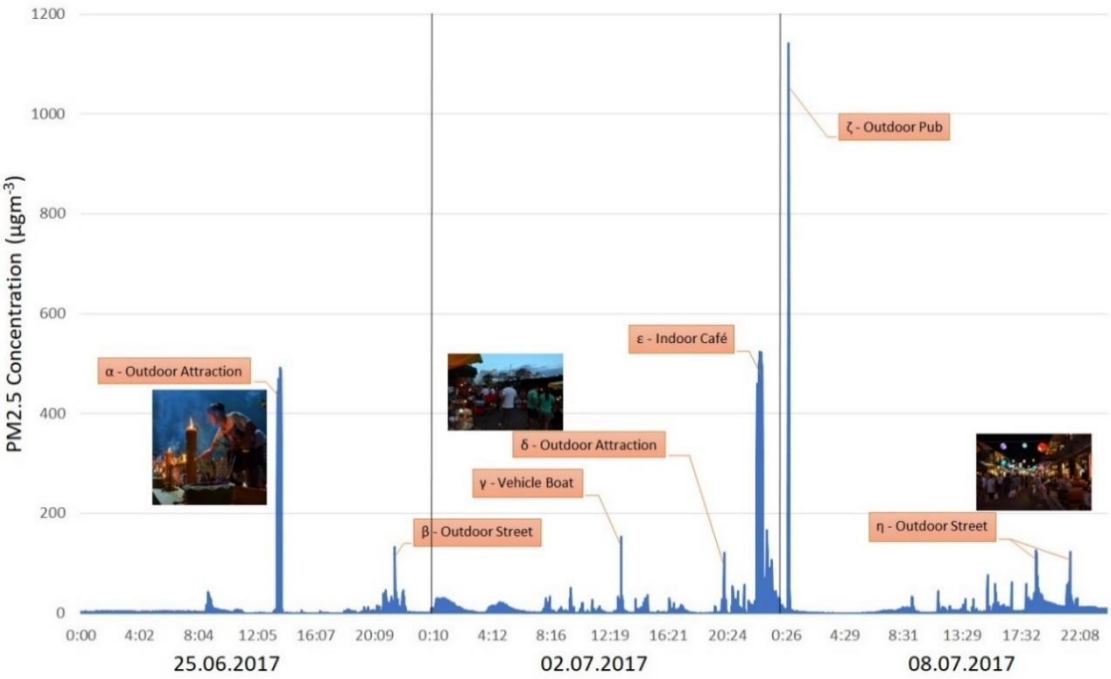

Figure 33. 1-minute averaged $PM_{2.5}$ concentrations in the various microenvironments for selected days (June 25, 2017 / August 2, 2017 / August 8, 2017) and the possible reasons and explanations for the recorded high concentrations.

α → Outdoor – Attraction, min242 max492 µg/m³ (19), Probable Reason: Burning Candles & Incense;
β → Outdoor – Street, min35 max133 µg/m³ (15), Probable Reason: Cooking
γ → Vehicle – Boat, min35 max154 µg/m³ (5), Probable Reason: Vehicle Exhaust;
δ → Outdoor – Attraction, min42 max121 µg/m³ (4), Probable Reason: Vehicle Exhaust, Road Dust
ε → Indoor – Café, min302 max525 µg/m³ (25), Probable Reason: Hookah Smoke, Tobacco Smoke;
Outdoor – Café, min35 max166 µg/m³ (45), Probable Reason: Hookah Smoke, Tobacco Smoke
ζ → Outdoor – Pub, min49 max1142 µg/m³ (8), Probable Reason: Tobacco Smoke;
η → Outdoor – Street, min35 max127 µg/m³ (23), Probable Reason: Vehicle Exhaust, Road Dust

Table 6 summarizes annual mean ambient $PM_{2.5}$ concentrations of traveled countries from various data sources such as The Organization for Economic Co-operation and Development (OECD), the World Health Organization (WHO), The World Bank, State of Global Air, and the Southeast Asia study result. As can be seen from the table, all recordings from the study are lower than the countries' yearly statistics from the given sources. Although $PM_{2.5}$ concentration values from the Southeast Asia study are very similar to the United States and Singapore, and relatively similar to Cambodia, they are not well matched with WHO's country statistics shown in Table 6. Moreover, the same pattern is observed when the Southeast Asia study's outdoor 1-hour mean $PM_{2.5}$ concentrations are compared to WHO's country statistics except in the United States, Singapore, and Qatar where concentrations are lower for the United States, higher in Singapore, and there is no outdoor data for Qatar.

Table 6. Annual mean ambient $PM_{2.5}$ concentrations from various data sources and 1-hour mean $PM_{2.5}$ concentrations from Southeast Asia study for the traveled countries.

Country	$PM_{2.5}$ Data Source ($\mu g/m^3$)					
	OECD α	WHO β	The World Bank γ	State of Global Air δ	SE Asia Study ε	SE Asia Study Out. ζ
Thailand	28.9	24.6	26.4	26	9.6	13.1
Cambodia	18.7	23.0	29.0	29	14.7	20
Singapore	30.8	17.0	18.7	19	16.5	21.4
Taiwan	*48.8	*54.3	*58.4	30	10.9	15.4
Hong Kong & Macau	*48.8	*54.3	*58.4	58	16.0	22.2
Qatar	89.2	103.4	107.3	107	12.4	-
The United States	10.9	8.2	8.4	8	6.7	4.5

α → OECD's 1-year mean $PM_{2.5}$ concentration data belongs to the year of 2015.
β → WHO's 1-year mean $PM_{2.5}$ concentration data belongs to the year of 2014.
γ → The World Bank's 1-year mean $PM_{2.5}$ concentration data belongs to the year of 2015.
δ → State of Global Air's 1-year mean $PM_{2.5}$ concentration data belongs to the year of 2015.
ε → 1-hour mean $PM_{2.5}$ measurements from Southeast Asia study.
ζ → Outdoor microenvironments 1-hour mean $PM_{2.5}$ measurements from Southeast Asia study.
*China's average $PM_{2.5}$ concentration value was used because of limited data related to Taiwan, Hong Kong, and Macau.

Figure 34 shows WHO's suggested 24-hour mean $PM_{2.5}$ concentration limit as a green line which at 25 $\mu g/m^3$, WHO's annual mean ambient $PM_{2.5}$ concentration data for each country as a red triangle, and 1-hour mean $PM_{2.5}$ concentrations from the Southeast Asia study in the traveled countries as a blue square which was shown in Table 6. The probable reasons for low $PM_{2.5}$ concentration values compared to WHO's annual mean statistics are having only indoor measurements at the airport in Doha, Qatar, relatively good ambient air quality due to monsoon season which affects the air quality positively, other meteorological factors such as temperature, humidity, precipitation, wind speed, and wind direction which yielded lower $PM_{2.5}$ concentration values in Thailand, Taiwan, Hong Kong & Macau at that time of the year, and at last but not least, it may be related to having low performance of the monitor during those measurement periods as compared to FMSs.

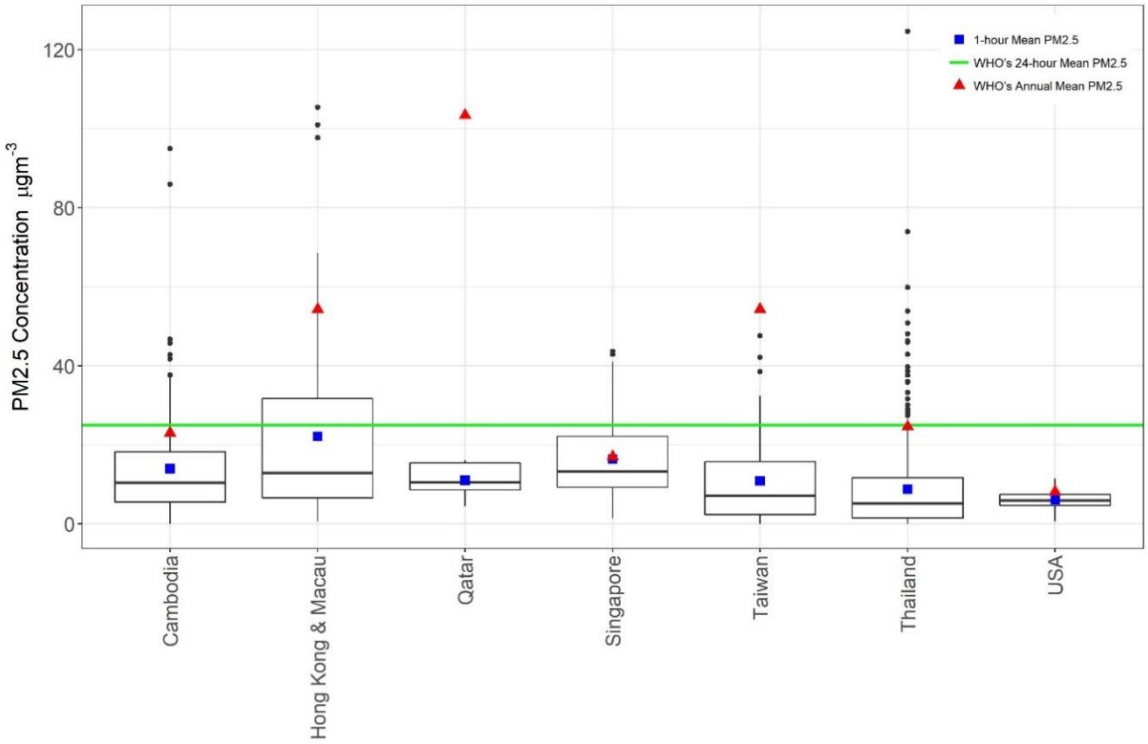

Figure 34. 1-hour mean $PM_{2.5}$ concentrations in different countries and their comparison to WHO's suggested 24-hour mean $PM_{2.5}$ concentration limit and annual mean ambient $PM_{2.5}$ concentrations of studied countries.

Web-based low-cost monitors data from OpenAQ are used and compared to our Southeast Asia findings for Taiwan and the United States by choosing the closest stations and similar travel dates and times in Figure 35. These were the only available countries that OpenAQ has low-cost monitor users and $PM_{2.5}$ recordings. According to data from those low-cost sensors and the assembled monitor which was used in our study, the results matched well for the United States and Taiwan datasets.

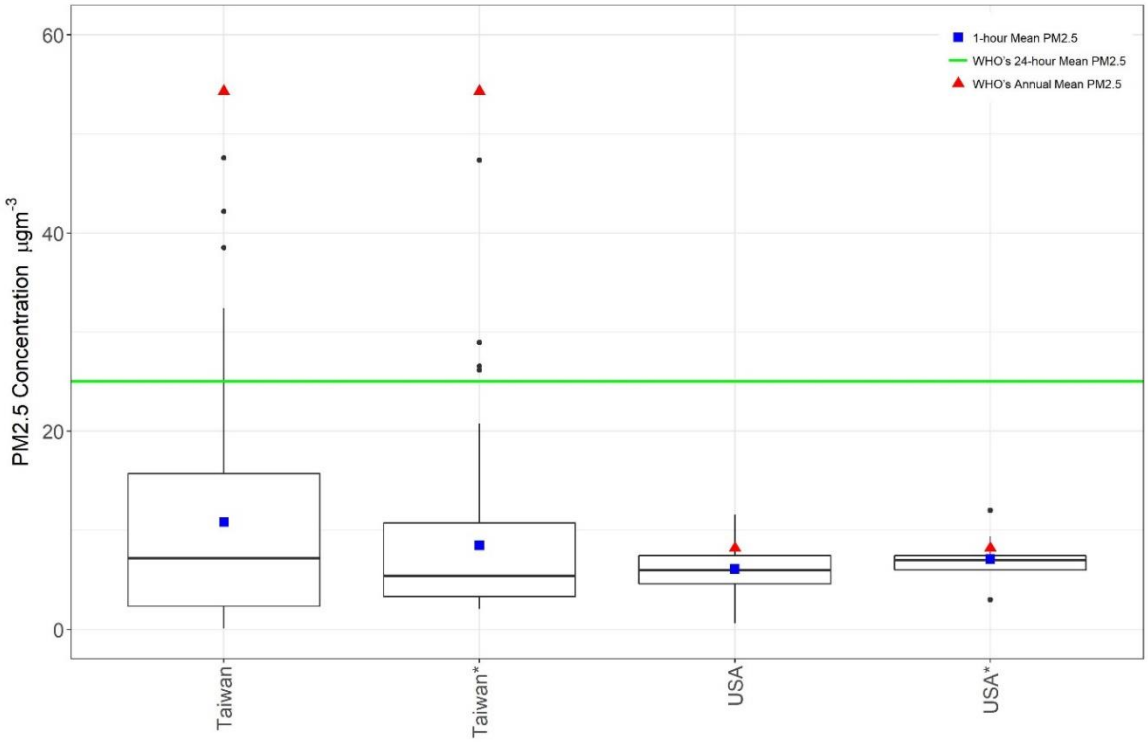

Figure 35. 1-hour mean $PM_{2.5}$ concentrations from Southeast Asia study and OpenAQ for Taiwan and the USA and their comparison to WHO's suggested 24-hour mean $PM_{2.5}$ concentration limit and annual mean ambient $PM_{2.5}$ concentrations for Taiwan and USA from WHO.

Taiwan* → The data is taken from OpenAQ from Songshan station in Taipei, Taiwan between 21.09.2017 13:00 – 24.09.2017 08:00. (Original days; 21.07.2017 – 24.07.2017)

The United States* → The data is taken from OpenAQ from Desplns station in Chicago, IL between 30.07.2017 14:00 – 30.07.2017 16:00 and Madison East station in Madison, WI between 30.07.2017 17:00 – 31.07.2017 00:00.

In addition, Figure 36 informs us that the Southeast Asia study's 1-hour mean $PM_{2.5}$ concentrations for 3 microenvironments are less than WHO's 24-hour mean $PM_{2.5}$ exposure limits. Indoor, outdoor, and vehicle microenvironments' $PM_{2.5}$ concentrations are 9.8, 16.1, and 13.5 µg/m^3, respectively.

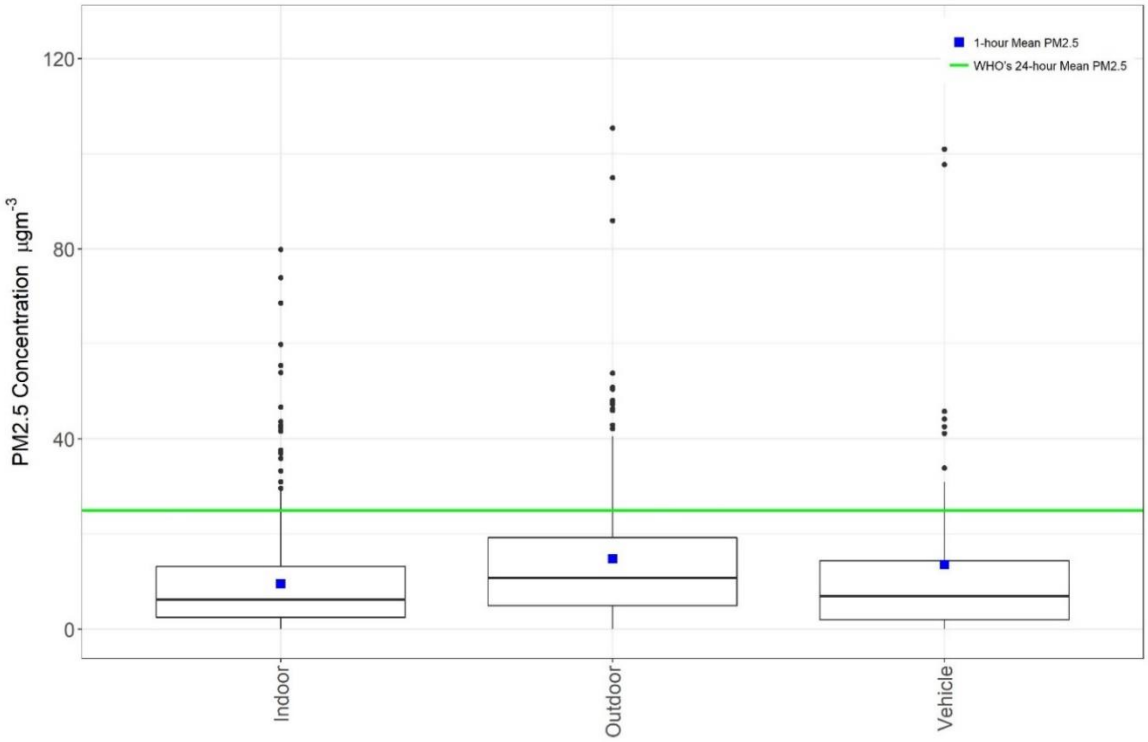

Figure 36. 1-hour mean $PM_{2.5}$ concentrations in 3 microenvironments and their comparison with WHO's 24-hour mean $PM_{2.5}$ exposure limits.

The microenvironments approach is important for understanding the effects of environments on personal $PM_{2.5}$ exposure. Despite spending a relatively small amount of time in microenvironments that have high pollutant concentrations, they may be a significant predictor of 24-hour mean personal exposure (Strak et al., 2010; de Nazelle et al., 2012). One study in Flanders, Belgium showed that spending 6% of volunteers' time in the different travel modes resulted in 21% of the total personal exposures and 30% of the total inhaled dose in a single day (Dons et al., 2012).

Figure 37 illustrates the Southeast Asia study's 1-hour mean $PM_{2.5}$ concentrations for 17 microenvironments. The average $PM_{2.5}$ concentrations for the 17 microenvironments varied between 2.3 and 32.8 µg/m^3. According to the findings of this study, the most problematic/polluted microenvironments are Port/Station (outdoor) and Café/Pub/Restaurant (indoor-outdoor) with 32.8 and 29.6 µg/m^3, respectively. The main reasons for measuring high concentrations of $PM_{2.5}$ in these microenvironments were proximity to tailpipe emissions from transportation sourced combustion engines such as cars, buses, boats, ferries, and light-duty vehicles and emissions from food cooking/baking

activities. Market/Shopping Mall (indoor), Street (outdoor), and Cable Car/Metro/Tram (vehicle) were the second most concerning microenvironments after measuring 19.3, 19.3, and 18.9 µg/m^3, respectively. Interestingly, the Passenger Car (vehicle) microenvironment had the lowest $PM_{2.5}$ concentration with 2.3 µg/m^3. This both agrees and disagrees with some studies on transportation microenvironments in the literature (Knibbs et al., 2010; Wang et al., 2011; Kaur et al., 2005; de Nazelle et al., 2012). During the transportation, air conditioning was always on and it is highly likely that the used car had an effective filter system for particle removal which resulted in low $PM_{2.5}$ concentrations and exposure compared to other microenvironments.

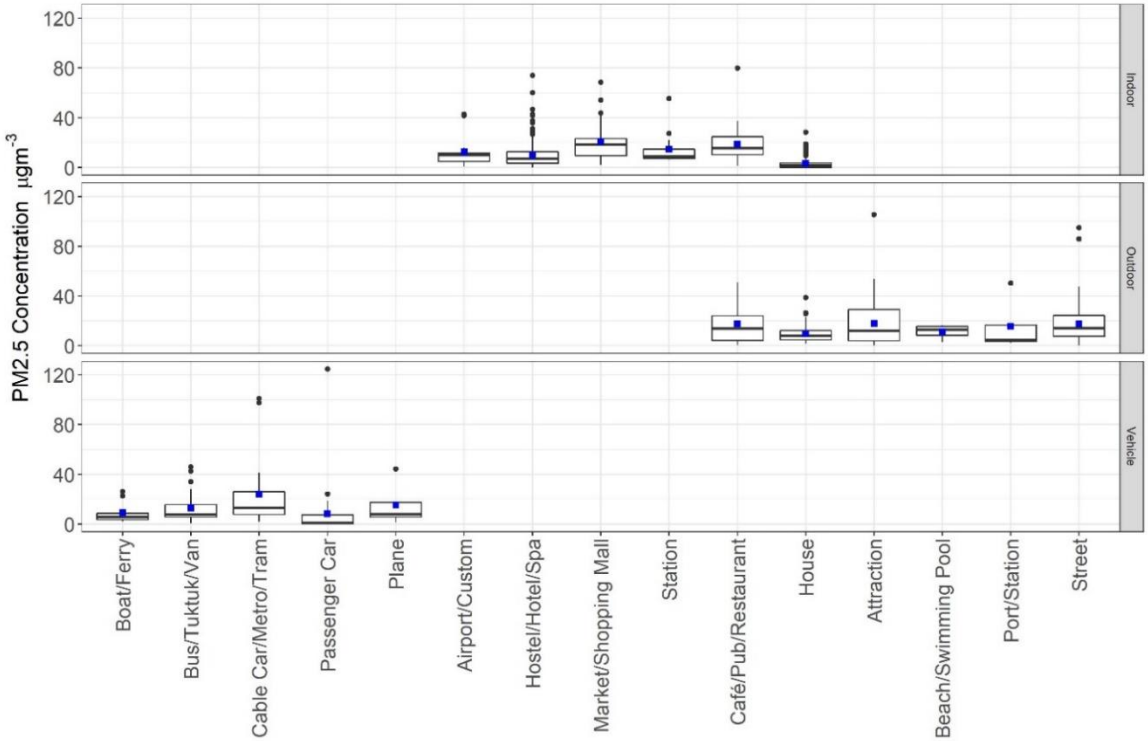

Figure 37. 1-hour mean $PM_{2.5}$ concentrations in 17 sub-microenvironments in this study.

As can be seen from the results, $PM_{2.5}$ concentration measurements (µg/m^3) are given in 1-hour mean format but WHO's guideline value is in the 24-hour mean. It seems an inappropriate way to compare 1-hour personal exposure values to WHO's 24-hour ambient guideline value directly, due to the limited applications and data of personal exposure studies for each microenvironments that were listed in this study and short-term measurement in some of the microenvironments during the study period, it is the only applicable way to compare measured concentrations. By comparing the measurement

results in the listed microenvironments to WHO's guideline value, each microenvironment can be categorized as polluted, concerned or not-concerning. This gives a broad idea and helps for understanding the effects and dynamics of these microenvironments on presented $PM_{2.5}$ concentration levels. Moreover, it is generally true that long-term and short-term measurements may be correlated to each other in some cases and studies, so we believe that applying this approach to this study is acceptable.

Moreover, multiplying 1-hour mean $PM_{2.5}$ concentrations by the time spent in each microenvironment gives $PM_{2.5}$ exposure in µg-hour/m^3 (in Table 5). It helps us to understand which microenvironment is dominant during our study. Unsurprisingly, the Hostel/Hotel/Spa microenvironment had the highest exposure due to having the highest time spent, 32%, even though it has a relatively low-level 1-hour mean $PM_{2.5}$ concentration. The Street microenvironment was the second highest $PM_{2.5}$ exposure, having a relatively high 1-hour mean $PM_{2.5}$ concentration, although less time was spent there, 11%. Interestingly, the Café/Pub/Restaurant and House microenvironments had the third highest $PM_{2.5}$ exposure, 1,449.4 µg-hour/m^3 and 1,426.6 µg-hour/m^3, respectively. The Café/Pub/Restaurant microenvironment was one of the most polluted environments and just 6% of the recording time was spent there. The House microenvironment had a relatively low 1-hour mean $PM_{2.5}$ concentration, but one of the highest recording times, 27%. It is obvious that personal exposure has a strong correlation with ambient $PM_{2.5}$ concentrations and time spent in the different microenvironments, both determine the daily exposure of $PM_{2.5}$ in an individual person.

6. DISCUSSION

Low-cost sensing provides advanced spatial and temporal variability exposure datasets which helps to improve the characterization of air pollutants, air pollution levels, exposure patterns, and increase the quality of exposure models via representative personal exposure studies. These datasets allow environmental health scientists, epidemiologists, and allergists to have current knowledge of air pollution levels and trends in order to advise their patients accordingly (White et al., 2012). They can advise their patients to minimize their outdoor activities during days with high pollution levels to avoid harmful effects and recommend them to review their indoor activities and pollution sources to manage their indoor exposure levels. Our measurements showed that some microenvironments are concerning due to higher $PM_{2.5}$ concentrations. Sensitive people should spend less time in these microenvironments in order to limit their $PM_{2.5}$ exposure. Moreover, by sharing air pollution and quality results with the public via mobile phone applications or the internet, sensitive people, especially those already at risk, can plan their outdoor activities, check their residential areas' and workplaces' air quality and may choose new residential locations or workplaces which are away from localized air pollution sources. Individuals may also make decisions about which countries/cities to travel based on pollution data (Bernstein et al, 2004). An environmentally sensitive tourism approach, defined by choosing less polluted, more environmentally friendly, and sustainable developed countries/cities will create economic pressure on countries/cities with higher $PM_{2.5}$ pollution levels not to lose their share of the tourism industry. Furthermore, patients, doctors, patient advocates, engineers, and environmentalists who support clean air movements can push governments and environmental agencies to implement stricter and more science-based air pollution standards and regulations.

As noted in previous studies, the low-cost sensors need more improvement and further studies to understand their technological limitations and to overcome their drawbacks. They are not as accurate or as consistent as FMSs and can be affected by meteorological conditions such as temperature, humidity, precipitation, wind speed, and wind direction, seasonal variations, chemical composition of $PM_{2.5}$ and other factors (Gao et al., 2015; Wang et al., 2015). They have relatively short operational time because of their fragility under diverse and extreme environmental conditions (Kumar et al., 2015). This

issue leads to another environmental concern, the additional burden of electronic-waste management because of the low-cost monitors' short-term operational time. Furthermore, maintenance, data management, analysis, post-processing, and visualization costs can exceed the cost of the actual monitor itself (Kumar et al., 2015). Low-cost sensing introduces opportunistic sensing under the banner of citizen science which can cause another challenge in addition to present ones. $PM_{2.5}$ and other pollutants' concentration values have been collecting and posting online. Some concerns include managing the enormous amount of data collected by the monitor networks, transparency of the recorded concentrations and organizations, and access possibilities to them as users, citizens, scientists, and government officials. In addition, without giving proper information and training to users, concentration measurements may cause unnecessary public concern or complacency about real air pollution levels. Lastly, they are also vulnerable to manipulation which may create unrealistic datasets that cause public pressure on environmental agencies with or without purpose.

Limitations of our study include working with just one traveler, using one monitor to sample the $PM_{2.5}$ concentration, not having a perfect design of the low-cost monitor, potential airflow perturbations when the monitor was used in the side pocket of the backpack, a lack of any co-location study with traditional monitoring stations to compare the $PM_{2.5}$ readings with a robust reference instruments, and also the effect of environmental variables (weather patterns, chemical compositions of $PM_{2.5}$). Several aspects of this study can be addressed in future work such as: encouraging researchers to set up personal exposure studies, raising awareness to the effects of microenvironments and people's activities on potential exposure, extending measurements to a longer time frame, using more low-cost monitors and working with more travelers to have more spatial coverage, increasing the study area to other countries and continents, considering dose calculation for individual travelers, and examining particle composition and toxicity of $PM_{2.5}$.

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Figure 11: https://ourworldindata.org/grapher/death-rate-by-source-from-air-pollution

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