INVESTIGATING LOCALIZED AIR POLLUTION EXPOSURE IN THESSALONIKI, GREECE

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Abstract

The regional monitoring stations in Thessaloniki inadequately represent the localized exposure to indoor and outdoor air pollutants. Our study examined concentrations at a finer scale through the portability of micro-sensors. We also aimed to understand the perceptions of café and restaurant workers to effectively communicate personalized results and provide feasible recommendations for reducing their exposure. Our analysis revealed smoking and weather to be the most influential on ambient pollutant levels, and we found a limited understanding of air pollution among employees. We recommend further micro-sensor use to investigate additional scenarios for personal exposure. Our work also suggests that more stakeholder interaction could increase awareness and understanding of air pollution.

Executive Summary

Background

According to the European Environmental Agency, the most significant environmental health risk to residents of Europe is air pollution (European Environmental Agency [EEA], 2022). Our partner, the Environmental Science Department at Perrotis College in Thessaloniki, was interested in increased data collection to develop a complete assessment of localized pollution exposure. The National Air Pollution Monitoring Network (NAPMN) includes seven national government-run sensor locations in the greater Thessaloniki area (Greek Ministry of Environment and Energy, 2019). The 2 km^2 resolution of mapping provided by station data inadequately represents exposure because pollution levels in outdoor urban environments can significantly vary within 100 meters (Briggs, 1997).

Vehicle emissions and industrial activity are contributors to Thessaloniki's air pollution and are associated with NO_2 and particulate matter (PM) (Valavanidis et al., 2015, Matthaios et al., 2017, Moussiopoulos et al., 2009). Indoor air quality is affected by human activities such as smoking and cooking (Vardoulakis et al., 2020, Tran et al., 2020). Studies in Thessaloniki have found a disproportionate number of hospitalizations, pharmaceutical therapies, and absences from work compared to other European cities due to the high levels of PM_{10} (Valavanidis et al., 2015). Increased morbidity and mortality from exposure to high concentrations can be organized into three main categories: neurological, cardiac, and respiratory, including stroke, heart attacks, and chronic obstructive pulmonary disease (COPD). The World Health Organization bases guidelines on the health impacts, but they are not legally binding. This is unlike the limits set in the European Union's Directive 2008/50/EC (EEA, n.d.).

Approach

We investigated cafés, restaurants, and public streets since these are significant locations in the lives of Thessaloniki residents. Neighborhoods of interest included Nikis, Egnatia, and the old district of Ano Poli. We collected data using two types of sensors: Atmotube PRO measured PM, and Envea Cairsens measured SO_2, NO_2, and CO concentrations.

Our goals, objectives and methods are displayed in Figure i below.

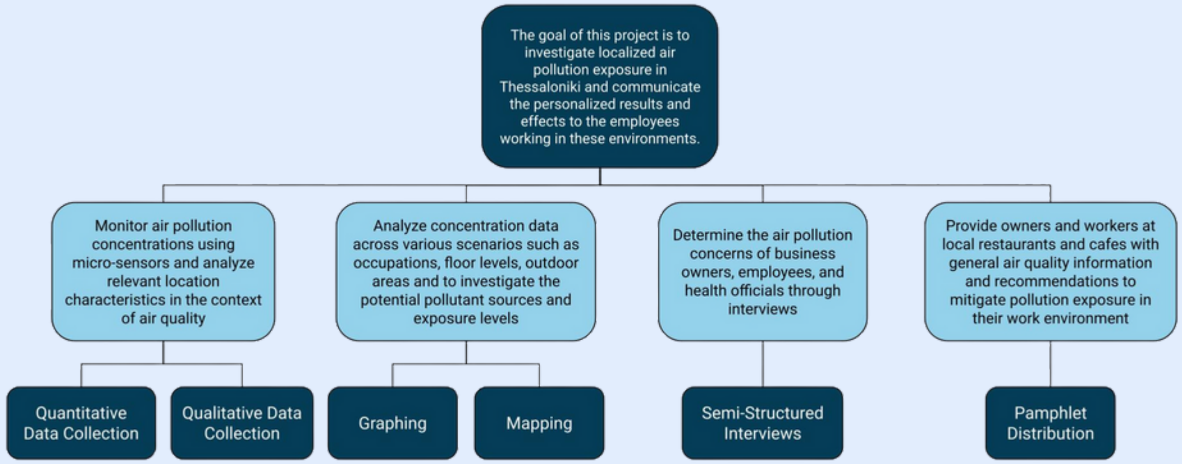

Figure i. A diagram depicting our goal, objectives, and methods

Our team monitored locations three days a week for three weeks. Each day we collected data from two cafés and two restaurants in one neighborhood. We took measurements in seating areas for up to two hours per location, mimicking the time a customer spends during a stay. To supplement the quantitative data, the team recorded qualitative observations using a Google Form to document variables that impact air quality. We characterized each location into four categories: indoor, fully-enclosed outdoor, semi-enclosed outdoor, and outdoor. Our team compared concentrations through visualization techniques such as graphing and mapping. We walked around downtown and pinpointed the timestamped coordinate locations with the measured values of pollutant concentrations from the Atmotube mobile application.

We conducted semi-structured interviews with business owners or employees to gauge their understanding of air pollution. Our questions investigated their opinions and current knowledge of pollution sources such as kitchens, people smoking outside, and vehicles. After collecting data from their business, we returned with a pamphlet that provided information on sources of pollution, health effects, mitigation techniques, further references, and personalized exposure levels from their data.

Findings

We found lower NO_2 concentrations in Ano Poli than downtown, while $PM_{2.5}$ concentrations were similar between neighborhoods.

We found unsafe levels of $PM_{2.5}$ in all neighborhoods, totaling 12 occurrences which exceeded the WHO 24-hour guidelines. NO_2 concentrations were above WHO 24-hour limits in Egnatia and Nikis. These findings are displayed in Figure ii below.

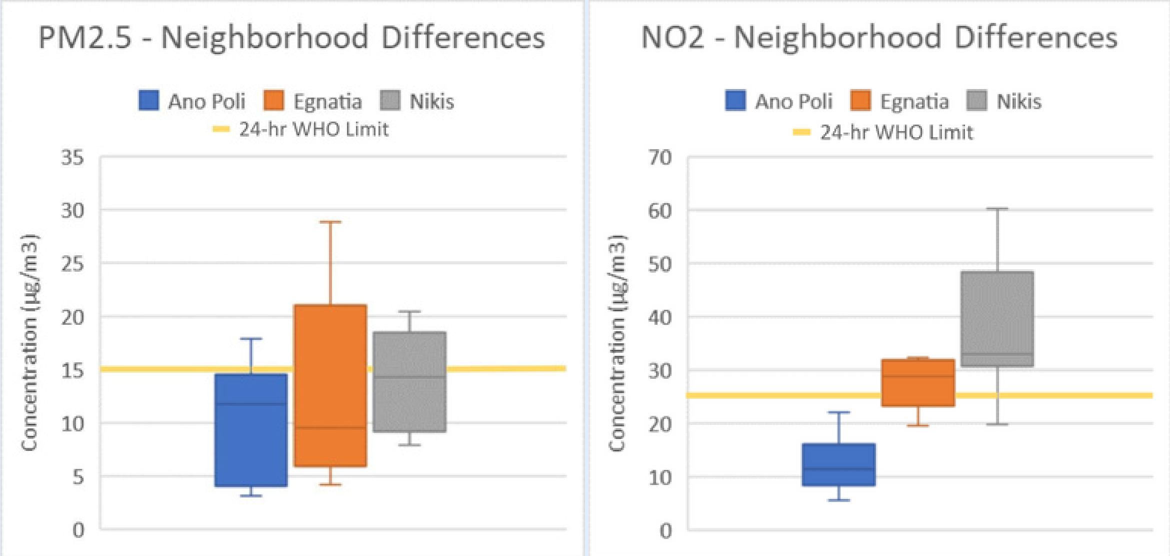

Figure ii. $PM_{2.5}$ and NO_2 concentrations are organized by the neighborhood of focus

Passive smoking and SO_2 were the most influential sources of high ambient pollution levels.

We noticed PM concentrations only exceeded EU limits near active smokers. SO_2 concentrations were constantly above WHO 24-hour limits at all locations, especially outdoors.

Low PM concentrations were found while walking around Egnatia and Nikis, while smoking caused large spikes.

Our team investigated several streets and discovered that most measured PM_{10} concentrations were lower than the WHO 24-hour guideline. Exceptions occurred due to spikes from smoking or atypical wind patterns. We created concentration density maps shown in Figure iii on the right.

Restaurant Employees experience concentrations of PM consistently above WHO guidelines.

Two in-depth studies on the exposure of kitchen staff found $PM_{2.5}$ levels consistently above WHO guidelines. Spikes were seen due to smoking, turning off ventilation, and cooking.

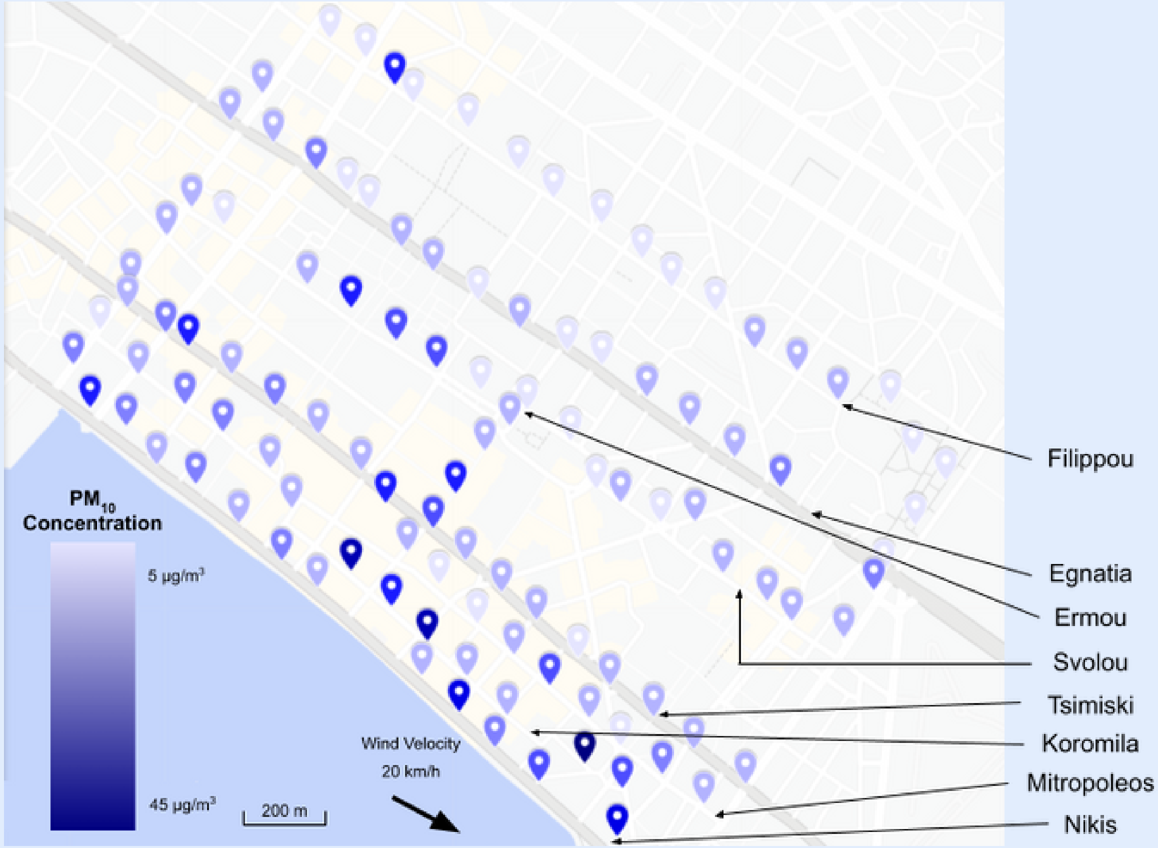

Figure iii. PM walking data of the Egnatia and Nikis areas on April 5

We found stakeholders have limited prior knowledge but a desire to learn more about air quality.

Many of the workers we interviewed had limited knowledge of air pollution sources and did not think they could make an impact to improve air quality. All the interviewees were interested to learn more about their exposure, so we created personalized pamphlets for our stakeholders.

We found using simplified language was effective in communicating about pollution.

Based on feedback from one stakeholder, we categorized CO, SO_2, and NO_2 as "Harmful Gasses" for simplicity and produced all pamphlets in Greek to reduce the language barrier.

Feedback from interviewees provided insight into the importance of raising awareness.

Feedback from pamphlet distribution revealed a limited awareness of health effects related to air pollution. Our most insightful conversation was with an interviewee that indicated there are social pressures on businesses to allow smoking to retain customers.

Recommendations

Increase local awareness and understanding of air pollution.

Based on our interviews about the perceptions and opinions on air pollution, workers in restaurants and cafés have limited awareness and understanding of air pollution. We recommend expanding outreach through the distribution of an informative pamphlet. We also recommend increasing public awareness by local government officials implementing an alert system to inform residents when pollution levels exceed WHO guidelines and EU limits.

Suggestions for future research

We recommend an in-depth study of four distinct facets of future research.

1. **Collect Data for Large-Scale Consumer Exposure.** This would eliminate the effect of external conditions such as weather and wind.
2. **Compare Restaurant Employee and Customer Exposure.** This data could compare different kitchen configurations and their effectiveness at improving air quality.
3. **Investigate Household Exposure Across Thessaloniki.** This could suggest safer places for residents to live or identify marginalized communities.
4. **Perform Data Verification and Comparison.** After verification, compare station data with locations farther away to reveal where published air quality is misrepresentative.

Improve the use of micro-sensors for a personal exposure study.

After several weeks of data collection, we learned strategies that improved micro-sensor effectiveness. Taking detailed qualitative notes coinciding with qualitative data can attribute concentration spikes to a source. We found a live feed of measurements to be especially useful. For future studies, these strategies will improve data collection and source identification.

Perform a more in-depth study focusing on the contributions to ambient concentration levels.

The only identifiable sources for spikes in PM or gasses were passive smoking and automotive traffic, respectively. Further research could involve studying Thessaloniki's wind patterns and investigating the contributions from the industrial centers, the port, and residential heating. With proper source attribution, researchers could provide further personalized solutions to stakeholders.

Acknowledgments

Our team would like to thank everyone who contributed towards completing this project. Without their help, this project would not have been possible.

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Meet the Team

I'm Mikaela Enax, a third-year student studying biomedical engineering and on a pre-medicine track at WPI. My interests in public health and science communication drew me to this project.

I'm Mark Gagliardi, a third-year student studying robotics engineering as well as electrical and computer engineering at WPI. My interests in sensors and learning outside of my field are what attracted me to this project.

I'm Alexander Lucero, a third-year student studying mechanical engineering at WPI with an interest in component test. My passions for data analysis and visualization drew me to this project.

My name is Alex Wadsworth, a third-year student studying mechanical engineering focusing on mechanical design and robotics. I'm interested in making the world a more sustainable place to live, which attracted me to this project.

This report is the result of an equal contribution from all authors.

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Introduction

"**A localized approach that collects data on pollutant levels from daily activities more accurately portrays the exposure residents face.**"

According to the European Environmental Agency, the most significant environmental health risk to residents of Europe is air pollution (European Environmental Agency [EEA], 2022). Specific pollutants of concern, such as particulate matter (PM) and harmful gasses, lead to irritation and damage to the cardiovascular and respiratory systems (Tran et al., 2020). In 2020, there were 52 exceedances of PM_{10} concentrations to the 24-hr limit value in downtown Thessaloniki, surpassing the EU 35-day limit (Progiou et al., 2023). Studies in Thessaloniki have found a disproportionate number of hospitalizations, pharmaceutical therapies, and absences from work compared to other European cities due to the high levels of PM_{10} (Valavanidis et al., 2015).

Our project partner, the Environmental Science Department at Perrotis College in Thessaloniki, was interested in increased data collection to develop a more complete assessment of localized pollution exposure. The current regional monitoring system consists of stationary sensors whose data is currently presented with a 2 km^2 resolution of mapped concentrations (Greek Ministry of Environment and Energy, 2019). However, concentration levels in outdoor urban environments can significantly vary within 100 meters (Briggs, 1997). Indoor air pollution also includes a complex combination of human and building characteristics with influence from the outdoor pollution (Vardoulakis et al., 2020). A localized approach that collects data on pollutant levels from daily activities more accurately portrays the exposure residents face.

The goal of this project was to investigate localized air pollution exposure in Thessaloniki and communicate the personalized results and effects to employees working in these environments. Due to the health effects associated with poor air quality, we investigated significant neighborhoods to the lives of Thessaloniki residents which were café, restaurant, and bar locations, as well as popular public streets. Our team recorded air pollutant concentrations with portable micro-sensors to fulfill our localized approach. The objectives were as follows:

- Monitor air pollution concentrations using micro-sensors and analyze relevant location characteristics in the context of air quality
- Analyze concentration data across various scenarios such as occupations and outdoor areas to investigate the potential pollutant sources and exposure levels
- Determine the air pollution concerns of business owners, employees, and health officials through interviews
- Provide owners and workers at local restaurants and cafés with general air quality information and recommendations to mitigate pollution exposure in their work environment

During the data collection process, we conducted site assessments at restaurants, cafés, and walking paths to identify relevant factors that may affect the pollutant concentrations. We conducted interviews with owners and employees to understand the local perceptions of the air quality at their businesses. Then, we utilized the micro-sensors to record pollutant concentrations for comparison with WHO guidelines and EU limit values and visualized the results. We provided personalized air quality results to inform employees who were interested in their exposure. Our team contrasted measured exposure with the perceptions of stakeholders to develop pamphlets containing generalized information on air quality resources. Finally, we provide recommendations for future researchers on how to conduct effective monitoring and ways to increase awareness of air pollution.

Figure 1. View of the White Tower looking down a side street from Tsimiski

Background

Thessaloniki & Air Pollution

Located in northern Greece, the prominent port of the Thermaic Gulf, Thessaloniki is the second-largest city in Greece in terms of population, industry, and economy (Psistaki et al., 2023). The gulf borders the city to the south, Mount Chortiatis or Hortiatis to the southwest, while the forest, Seih Sou, borders the northeastern area to create a 12 km bowl-shaped urban area (Flocas et al., 2009; Chatzigogos et al., 2006). A key meteorological feature of the region is the northwestern wind, Vardaris, that blows through the Axios Valley with consistent direction and high intensity. This is specifically known for the movement of cold, dry air with a powerful ability to cause damage to infrastructure (Koletsis, 2016).

The municipality is the city center and largest of the Thessaloniki Urban area with a population of 317,178 and makes up a third of the greater metropolitan area's total population of 1,091,424 in 2021 (Hellenic Statistical Authority, 2022). With a density of 20,429 inhabitants per km^2, the center is the most densely populated (Saliara, 2014). The social makeup of the region includes the historic center with a high proportion of residences and mixed social classes. The north and northwest are mainly working class, while the south and southeast are more middle class for the main compact urban area (Yiannakou et al., 2016) The east is mainly agricultural land and commercial hubs while the west is the industrial center. Major transportation arteries include Egnatia, Tsimiski, and Mitropoleos Streets which are utilized by the bus system (Saliara, 2014).

Figure 2. An aerial view of the city center, Thermaic Gulf, and surrounding mountains

Figure 3. A view of Mount Chortiatis

Note. Figure 3 is from Christaras, A. (2009). English: Mount Chortiatis in Thessaloniki prefecture, Greece. As seen from Thessaloniki Makedonia Airport Passenger Terminal (Southwestern aspect). [Photograph]. https://commons.wikimedia.org/wiki/File:Chortiatis_mountain_%28with_observatory_at_peak%29,_Thessaloniki_prefecture,_Greece_01.jpg (CC BY-SA 3.0)

The Thessaloniki region consistently has levels of pollutants above European Union Air Quality standards because of the impact of residential heating, industrial emissions, and vehicle emissions. As of 2019, Greece was tied with two other European nations in having the second-highest concentration of PM_{10} (Carratù et al., 2019). PM is a solid or liquid suspended in the air, and the combined mixture between PM and air can be referred to as aerosol. It is usually characterized by size, thus some common sizes are defined as being less than 10 micrometers and 2.5 micrometers (PM_{10} and $PM_{2.5}$, respectively). While many pollutants are present in Thessaloniki, PM is the most prevalent and is discussed extensively. These microscopic particles can be inhaled and penetrate deep into the lungs, even reaching the bloodstream (Environmental Protection Agency [EPA], 2022). This can significantly impact the lungs and heart leading to decreased function, irritation, and death from exposure to these particles (EPA, 2022).

Pollution Concentrations in Thessaloniki

To ensure health limits are not exceeded, directive 2008/50/EC of the European Parliament and Council sets limit values for pollutants. The directive has been revised making many limit values a legally binding regulation (Directive of the European Parliament, 2008). If limit values are exceeded, the commission can launch an "infringement procedure" and may refer the country to the Court of Justice of the European Union where financial restrictions can be imposed (Role of Member States, 2022). Indicative limits are not binding but are taken into account when mitigating policy is introduced. More information on the values of pollutant limits is provided in the table below.

In 2020, the European Commission decided to refer Greece to the Court of Justice of the European Union due to violations of the PM_{10} 24-hour limit. Thessaloniki had exceeded the limit values of PM_{10} on 67 days within the calendar year of 2019 (Commission refers Greece, n.d.). The official judgment of the court was made on March 23, 2023, and Greece was condemned for continued exceedances and lack of appropriate measures to reduce PM_{10}

Table 1. EU air quality directives

Pollutant	Averaging Period	Objective	Concentration	Comments
$PM_{2.5}$	Annual	Limit value	25 µg/m^3	
$PM_{2.5}$	Annual	Indicative Limit value	20 µg/m^3	
PM_{10}	24-hour	Limit value	50 µg/m^3	Max 35 days/yr
PM_{10}	Annual	Limit value	40 µg/m^3	
NO_2	1-hour	Limit value	200 µg/m^3	Max 18 hours/yr
NO_2	Annual	Limit value	40 µg/m^3	
SO_2	1-hour	Limit value	350 µg/m^3	Max 24 hours/yr
SO_2	24-hour	Limit value	125 µg/m^3	Max 3 days/yr
CO	Daily max 8-hour	Limit value	10 mg/m^3	

Note. Adapted from EU Air Quality Directives (2008/50/EC, 2004/107/EC) levels to below the EU daily limit (Lialias, 2023). In a study done by Hellenic Medicine, researchers used the United States Air Quality Index (AQI) as a valuation of pollutant concentrations to assess the air quality of Thessaloniki. AQI is calculated using concentrations of each pollutant ($PM_{2.5}$, PM_{10}, CO, NO_2, and SO_2), the highest value of AQI out of the group of pollutants is equal to the total AQI (United States Environmental Protection Agency [EPA], 2018). The contribution of each pollutant to the total AQI scores was analyzed, with PM being the responsible pollutant 66.5% of the time from 2011 to 2019 (Psefteli et al., 2021). Pollutant distributions within Thessaloniki vary by neighborhood. Urban traffic locations in 2020 measured 24-hour averages of 47 $\mu g/m^3$, just under the 50 $\mu g/m^3$ limit, while suburban background stations measured considerably less at 35 $\mu g/m^3$ (EEA, 2021).

Another important measure is the WHO air quality guidelines which are based on expert evaluation and scientific data. These measures are not enforceable, but serve as a “global target for national, regional and city governments to work towards improving their citizen’s health by reducing air pollution” (WHO, n.d., para. 2). The relevant target values are listed in the table below.

Table 2. WHO air quality guidelines

Pollutant	Averaging Period	Concentration
$PM_{2.5}$	24-hour	15 $\mu g/m^3$
PM_{10}	24-hour	45 $\mu g/m^3$
NO_2	24-hour	25 $\mu g/m^3$
SO_2	24-hour	40 $\mu g/m^3$
CO	Daily max 8-hour	4 mg/m^3

Note. Adapted from WHO Air Quality Guidelines 2021

Sources of Outdoor Air Pollution

Vehicle emissions are among the largest contributors to the city's air pollution. The pollutants in Thessaloniki that have been associated with vehicle emissions are NO_2 and PM (Valavanidis et al., 2015). In a report published in 2021, Karageorgou et al. from the Aristotle University of Thessaloniki analyzed the air pollution experienced by commuters in Thessaloniki. In a study produced by the university’s Department of Chemistry, PM was found to have high concentrations along the major traffic areas in the Municipality (Karageorgou et al., 2021). This study found that while commuters in cars and buses are exposed to harmful pollutants on dense roadways, people traveling on the sidewalks face disproportionately higher pollutant concentrations.

In addition to emissions from vehicles, biomass burning is a significant source of air pollution in Thessaloniki. A study from 2011 utilized two stations over two years, and researchers discovered average seasonal concentrations of PM were 1.1-1.6 times higher in the winter (Kassomenos et al., 2011). This seasonal variation leads to harmful levels of pollution during the winter months and its primary cause is biomass burning in the form of residential heating. Despite the gradual introduction of natural gas and heating oil to Greek residences, many people rely on wood fireplaces to combat the cold of the winters. This number significantly increased during the economic crisis in Greece, starting in the winter of 2010, when much of the environmental protection legislation and policies were repealed or deferred in an attempt to improve the economy. As the prices for natural gas and heating oil began to rise, this forced people to revert to using the more economical option of wood and even garbage (Valavanidis et al., 2015).

Another substantial source of air pollution in Thessaloniki is the presence of industrial centers located in the region. In 2007, PM_{10} was identified around the main industrial centers in northern, western, and northwestern Thessaloniki (Diapouli et al., 2017). Because of its unique geographic location, as described previously, Thessaloniki has several wind patterns that circulate emissions in the municipality where the main source of pollutants is fuel oil (Saraga et al., 2019). Many of these industrial centers are used for oil refining and petrochemical production (Bourliva et al., 2018). In an air monitoring study in Thessaloniki, researchers concluded that about 58-65% of PM_{10} concentrations came from the urban-industrial districts of the city (Matthaios et al., 2017). In addition to PM_{10}, the Thessaloniki industrial centers were identified to be the second leading cause of NO_x emissions (Moussiopoulos et al., 2009).

Sources of Indoor Air Pollution

While a majority of studies focus on the effects of outdoor air pollution levels, indoor air pollution also poses considerable harm to human health. Europeans are estimated to spend 90% of their time inside with two-thirds of that time spent in their household (Sarigiannis, n.d.). Often in Thessaloniki, when outdoor pollutant concentrations exceed the EU air quality standards, residents of the Municipality are instructed to go indoors to reduce exposure to the pollution. However, seemingly safe indoor environments produce SO_2, CO, NO_2, and PM which are some of the same aerosols that are outdoors (Tran et al., 2020). Sources of indoor air pollution include human activities, building materials, and emissions from household items, as well as outdoor factors, such as filterless ventilation units that can transport outdoor contaminants inside. Human activities include smoking, cooking, and using chemical cleaning supplies. Household items, such as candles and gas heating sources contribute to the decrease in indoor air quality through the production of PM and NO_2 respectively. (Tran et al., 2020).

Researchers from Aristotle University in Thessaloniki found that deep-frying food or cooking without using the ventilator increases the amount of PM present in the air. The measurements reported PM concentrations as high as 600 $\mu g/m^3$ (Kassandros et al., 2021). This was about 12 times greater than the levels of PM experienced before the cooking began and 13 times greater than the WHO guideline of 45 $\mu g/m^3$. Exceedance of this level can harm the respiratory and immune systems when the particles enter the body (WHO, 2022). A similar study examined PM_{10} and $PM_{2.5}$ levels in restaurant kitchens on the scale of a week. They found mean and maximum values for $PM_{2.5}$ to be 548.1 $\mu g/m^3$ to 5,172.1 $\mu g/m^3$ and for PM_{10}, 631.6 $\mu g/m^3$ to 113.1 $\mu g/m^3$ (Chang et al., 2021). The average concentrations are remarkably higher than the 24-hour WHO guidelines of 15 and 45 $\mu g/m^3$ for $PM_{2.5}$ and PM_{10}. In addition to PM, the use of electric alternatives for cooking also produces the pollutants, NO_2 and CO.

Air Pollution Mitigation

Exposure Mitigation in Restaurants

As discussed previously, exposure to harmful smoke and pollutants is mostly from cooking fuels, stoves, and cooking behavior. Strategies to mitigate the impact of pollution focus on either a substitute for these emitters or changes to kitchen design. Substituting fuels or cooking equipment for more efficient and “greener” options is one way to mitigate pollution exposure. The most common fuels for cooking in Greece are coal, liquid petroleum gas (LPG), natural gas, and electricity (Fameli et al., 2022).

These sources emit PM as well as CO with the exception being electricity which has no pollutant emission during use. Use of coal while grilling, is responsible for 98.1% of PM cooking emissions in Greece, while NO_2 is primarily from gas (LPG or natural gas) stoves which emit 68.9% of total NO_2 cooking emissions in Greece (Fameli et al., 2022). Restaurants that limit the use of coal and replace cooking equipment with electric systems will reduce exposure to PM and NO_2

Improved ventilation is also a feasible approach to improve kitchen air quality. In a study comparing different ventilation systems to no ventilation in a small apartment over short periods, using a kitchen hood resulted in a 93.9% reduction in PM concentrations (Pantelic et al., 2023). While larger airflow is more effective for ventilation, systems with a flow of 1.0 to 1.5 m/s are generally recommended (Cao et al., 2017). A simple action such as opening a window, or using a fan have proven to help circulation and improve kitchen air quality.

Air cleaning systems are crucial to reducing indoor air pollutant concentrations, specifically controlling the exposure of restaurant staff and customers. Laumbach (2015), an associate professor of environmental and occupational medicine at Rutgers University, states using standard central air filters, either media or electrostatic, can decrease the concentration of $PM_{2.5}$ indoors to 35% of the outdoor concentration. With the use of high-efficiency particulate air (HEPA) filters, this concentration change can be reduced to just 10% of the outdoor levels (Laumbach et al., 2015). Indoor air pollution can also be reduced by avoiding the use of paints, room fresheners, and cleaners that contain harmful chemicals (Dani et al., 2021).

Thessaloniki's History of Air Pollution Mitigation

The first major attempt to reduce air pollution banned diesel cars and the use of biomass to heat homes before 2011 (Grivas et al., 2020). The restriction on these fuels was lifted in Thessaloniki due to the economic crisis which began in 2009 and caused oil prices to surge (Saffari et al, 2013). Consequently, residents of dense urban areas turned to wood stoves and fireplaces as a source of heat (Gratsea et al., 2017). This burning of wood releases PM_{10}, causing extreme spikes in the concentrations of Thessaloniki's pollutant levels. According to Progiou (2023), the managing director of AXON Enviro-Group in Athens, 73% of all PM_{10} emissions in the city limits of Thessaloniki are a result of burning wood for heating. Additionally, the Greek Ministry of Health enacted a stricter smoking ban in 2010 after previous restrictions were ignored. Enclosed indoor spaces, specifically affecting bars and restaurants, were included in the ban. Violation of the law includes fines of up to €10,000 for businesses and €500 for individuals (Press, 2010).

Researchers from the Civil Engineering Department of Aristotle University conducted a specific study on the urban road networks and traffic characteristics of Thessaloniki to understand the exact breakdown of sources. They modeled concentrations of NO_x, and PM_{10} against traffic patterns and found that Thessaloniki had a car ownership index of 450 vehicles per 1000 residents with 57.5% of all traffic emissions coming from private cars alone. This is far above the EU average where around 12% of all emissions come from private vehicles (CO2 Emission Performance, n.d.).

Pollution levels have only slightly decreased in the past decade despite concern about minimal mitigation action (EEA, 2022). However, there are current efforts to reduce emissions within the city. Most notably, since 2007 a metro line has been under construction intending to provide transit to over 50,000 passengers a day (New Metro Thessaloniki, 2017). This project is funded by the European Regional Development Fund and the Greek government totaling an investment of up to €285 million (New Metro Thessaloniki, 2017). The reduction in private transportation is expected to prevent the release of 5000 tons of greenhouse gasses yearly (New Metro Thessaloniki, 2017). Many other proposals have been made as a response to the known issue of vehicle emissions. Requiring more eco-friendly vehicles and better maintenance of older vehicles would also limit emissions (Sarigiannis et al., 2017). Simpler forms of traffic control have also been considered such as a tax on vehicles driving within city limits. Petraki (2022), from the National Technical University of Athens, conducted a study on 733 Greek citizens about their opinions on a proposed traffic charge. This would include charges on vehicles relative to the burden they place on the public, meaning older or more polluting vehicles would receive a higher tax when entering city limits. Her results found that a majority of young and more intensive commuters are in support of these laws due to hopes that they will reduce congestion within the city (Petraki, 2022).

Health Effects of Air Pollution

The quality of air in urban settings, diminished by pollutants, poses "a major public health burden" (Pascal et al., 2013, p. 391), according to researchers after studying air pollution in 25 European cities. The WHO describes air pollution as the "greatest environmental threat to health and a leading cause of non-communicable diseases " (WHO, n.d., para. 2). The adverse health effects, based on the amount and length of exposure, emphasize the importance of being cognizant of pollutant levels. The adjacent table synthesizes studies on the health effects of exposure to air pollution.

Table 3. Summary of health studies and reviews on the impact of air pollution

Study	Location	Air Pollutant(s) of Focus	Health Effects & Impacts
Kakaletsis et al., 2016	Thessaloniki	NO_2	Increased levels of concentration of NO_2 were predictors of severe stroke
Kasdagli et al., 2022	Greece	$PM_{2.5}$, NO_2	Increased risk of mortality from cardiometabolic, COPD, and diseases of the nervous system; $PM_{2.5}$, NO_2, and BC were associated with increased mortality risk from nervous system diseases, cerebrovascular disease; Ischemic heart disease mortality risk increased from exposure to $PM_{2.5}$
Lee et al., 2020	-	$PM_{2.5}$	Increased risk of respiratory conditions such as chronic obstructive pulmonary disease (COPD) and lung cancer.
Paraliari et al., 2023	Thessaloniki	PM_{10}	Increased mortality for all-cause mortality and cardiorespiratory mortality when exposed to increased levels of pollutants.
Pascal et el., 2013	Athens, Greece & 24 other EU cities	PM	Pollution levels were reduced to the suggested levels, with an average life expectancy increase of 22 months at age 30 and saving €31 billion per year through health expenses and people absent from work
Tran et al., 2020	-	PM, NO_2, SO_2, CO_x	Irritation and damage of cardiovascular and respiratory systems; heart attacks, asthma, decreased lung function
Vardoulakis et al., 2020	-	$PM_{2.5}$ and PM_{10}, NO_2	Increased asthma symptoms and risk of lower respiratory infections

The Harm of Increased Pollutant Levels

To understand the impact of air pollution on the health of residents from 25 EU cities, including Athens, the Aphekom project provided comprehensive data on the effects of PM (Pascal et al., 2013). The project found an increase of up to 22 months of life expectancy for people aged 30 if the cities complied with the recommended annual mean of 10 μg/m^3 for $PM_{2.5}$ from WHO's 2005 standards. This has a long-term impact on the mortality of EU residents from chronic exposure. The long-term effects of complying with WHO air quality guidelines for pollution would save €31 billion per year by avoiding health expenses and work absenteeism (Pascal et al., 2013).

Morbidity caused by air pollution exceeding the EU limits was defined in years lived with disability (YLDs). The 2022 report on the health effects of air pollution from the European Environmental Agency found 175,702 YLDs from COPD caused by excessive exposure to $PM_{2.5}$. There were 175,070 YLDs from type II diabetes due to NO_2 exposure above EU standards with Greece having the third highest rate for YLDs caused by type II diabetes (EEA, 2022).

In Thessaloniki, an ecological study was conducted by researchers at Aristotle University, to assess the association between outdoor air pollution and acute ischemic stroke severity based on the relationship of stroke from pulmonary inflammation exacerbation due to air pollution. The researchers concluded that increased concentration levels of NO_2 were a predictor for increased severity of stroke by comparing the amount of pollution present near their residence on the day of hospital admission with the severity (Kakaletsis et al., 2016). Other work from Aristotle University and the National and Kapodistrian University of Athens investigated the short-term effects of air pollution on mortality in the greater Thessaloniki region. The 2023 study found that mortality increased by 2.3% and cardiorespiratory mortality specifically increased by 2% when the concentration of PM_{10} increased by 10 μg/m^3. The researchers also noted that the health impacts of air pollution are under-studied for Thessaloniki despite having high levels of pollutants like PM_{10} since most literature focuses on Athens (Parliari et al., 2023).

Effects of Indoor Air Pollution

The prior sources of indoor pollution result in the release of common pollutants, namely PM, NO_2, SO_2, and COx which lead to irritation and damage to the cardiovascular and respiratory systems (Tran et al., 2020). Lee et al. (2020) found household air pollution was associated with an increased risk of respiratory conditions such as chronic obstructive pulmonary disease (COPD) and lung cancer. Indoor increased levels of PM and NO_2 were associated with increased asthma symptoms and risk of lower respiratory infections (Vardoulakis et al., 2020). The WHO lists ischemic heart disease, stroke, lower respiratory disease, COPD, and lung cancer as the cause of 3.2 million deaths from exposure to household air pollution (WHO, 2022).

Despite the known associations between indoor air pollution and adverse health effects, researchers describe information on indoor pollution to be "sparse and less accessible " (Vardoulakis et al., 2020, pg. 14) than available outdoor pollution data (Vardoulakis et al., 2020; Sun et al., 2019). They recommend standardization of measuring and analyzing indoor air quality to better understand indoor air pollution levels and factors, particularly long-term data. There is a lack of standardization and analysis for indoor air quality compared to outdoors.

Long-term Exposure, Mortality & Morbidity

The health consequences of long-term exposure to air pollution, both indoors and outdoors, are associated with increased mortality and morbidity. A study by researchers from the Department of Hygiene, Epidemiology and Medical Statistics, Medical School at the National and Kapodistrian University of Athens, used the 2011 Census and predicted values of $PM_{2.5}$ and NO_2 to determine diagnosisspecific mortality. Their investigation assessed nervous system diseases such as cerebrovascular disease, ischemic heart disease, diabetes mellitus, and chronic obstructive pulmonary disease. An increased risk of mortality from cardiometabolic, COPD, and diseases of the nervous system was statistically determined when there is long-term exposure to air pollutants. $PM_{2.5}$, NO_2, was associated with increased mortality risk from nervous system diseases and cerebrovascular disease, while ischemic heart disease mortality risk increased from exposure to $PM_{2.5}$ (Kasdagli et al., 2022).

Psistaki et al. (2023), from universities in Thrace and Cyprus, investigated the potential hazards of PM and other pollutants in Thessaloniki and Limassol, Cyprus for a period between 1999 and 2016. The studies reveal that a 10 μg/m³ rise in $PM_{2.5}$ concentration leads to a 1.10% rise in mortality from cardiovascular-related illnesses (Psistaki et al., 2023). It was also determined that a 10 μg/m³ rise in PM_{10} concentration was associated with a 0.94% rise in mortality from respiratory-related illnesses (Psistaki et al., 2023). There was a higher pollutant concentration and mortality rate during the winter due to previously defined sources, such as residential heating (Psistaki et al., 2022). Valavanidis et al. (2015), who also performed a study in Thessaloniki, found a disproportionate number of hospitalizations, pharmaceutical therapies, and absences from work compared to other European cities due to the higher levels of PM_{10}. Vlachokostas et al. (2012) of the Laboratory of Heat Transfer and Environmental Engineering at Aristotle University investigated the Thessaloniki area for the adverse health effects of air pollutants. PM_{10} was measured in years of life lost for the overall Thessaloniki population and that value was determined to be at least 10,200 years (Vlachokostas et al., 2012). Not only is PM_{10} associated with increased premature mortality, but the study also found an increase of 450 cases of bronchitis in 2002 caused by air pollution (Vlachokostas et al., 2012)

Shortcomings in Air Pollution Monitoring in Thessaloniki

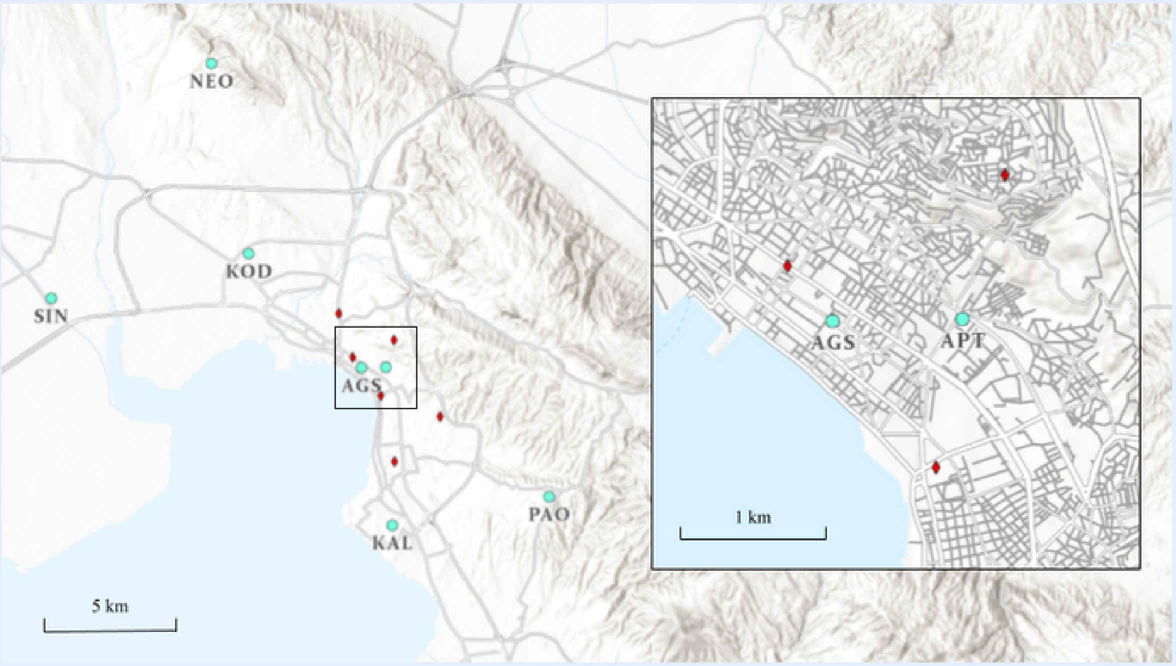

Figure 4: Monitoring stations in Thessaloniki

Note. Red is the municipal monitoring network, Blue is NAPMN with station acronym labels.

Existing Monitoring Networks and Limitations

The Greek Ministry of Environment and Energy established the National Air Pollution Monitoring Network (NAPMN) in 2001, expanding the existing network. This network includes 7 national government-run sensor locations in the greater Thessaloniki area. At these locations, pollutants are measured continuously throughout 24 hours with one measurement each minute. A microprocessor, located in each station, calculates hourly average pollution values. These sensors are calibrated using a standard sample of known concentration (Greek Ministry of Environment and Energy, 2019). The measurements are tabulated at each station and can be accessed by the public online in the form of a live map displaying concentration at each station.

The Environmental Department of the Municipality of Thessaloniki operates 6 Air Pollution and 9 Meteorological monitoring stations within the city limits. Each of the monitoring stations measures sulfur dioxide (SO_2), nitrogen monoxide (NO), nitrogen dioxide (NO_2), CO, PM_{10}, and $PM_{2.5}$. The locations are displayed in Figure 4.

One limitation of current monitoring systems is the limited number of $PM_{2.5}$ measurements, with only 2 locations in Thessaloniki that are run by the ministry. As discussed previously, $PM_{2.5}$ is an important pollutant to monitor because it can penetrate deep into the lungs and bloodstream, making it a cause of many respiratory conditions.

Monitoring is important to understand the prevalence of pollutants. $PM_{2.5}$ specifically, has already exceeded the indicative limit values; it is unknown if other regions of the city are experiencing similar or higher levels of these concentrations. Spatial approximations are the current methodology to determine city-wide exposure.

The Greek Ministry of Environment and Energy provides general regional pollution trends through visual concentration mapping of Greece. An inventory of emissions from all known sources has been carried out for the entire country with a resolution of 2 km by 2 km. Using advanced simulations, the model calculates atmospheric pollutant concentrations and displays the data as shown in Figure 5 (Greek Ministry of Environment and Energy, 2019).

Table 4. Measured pollutants at each NAPMN station

Station		Measured Pollutants				
Name	Characterization	SO_2	NOx	CO	PM_{10}	$PM_{2.5}$
Ag. Sofias (AGS)	Urban-Traffic	x	x	x	x	x
Aristotle (APT)	Urban-Background	x	x		x	
Panorama (PAO)	Suburban-Background		x		x	x
Kalamaria (KAL)	Suburban-Background	x	x	x	x	
Kordelio (KOD)	Urban-Industrial	x	x	x	x	
Sindos (SIN)	Urban-Industrial	x	x	x	x	
Neochorouda (NEO)	Suburban-Background		x		x	

Adapted from the Greek Ministry of Environment and Energy

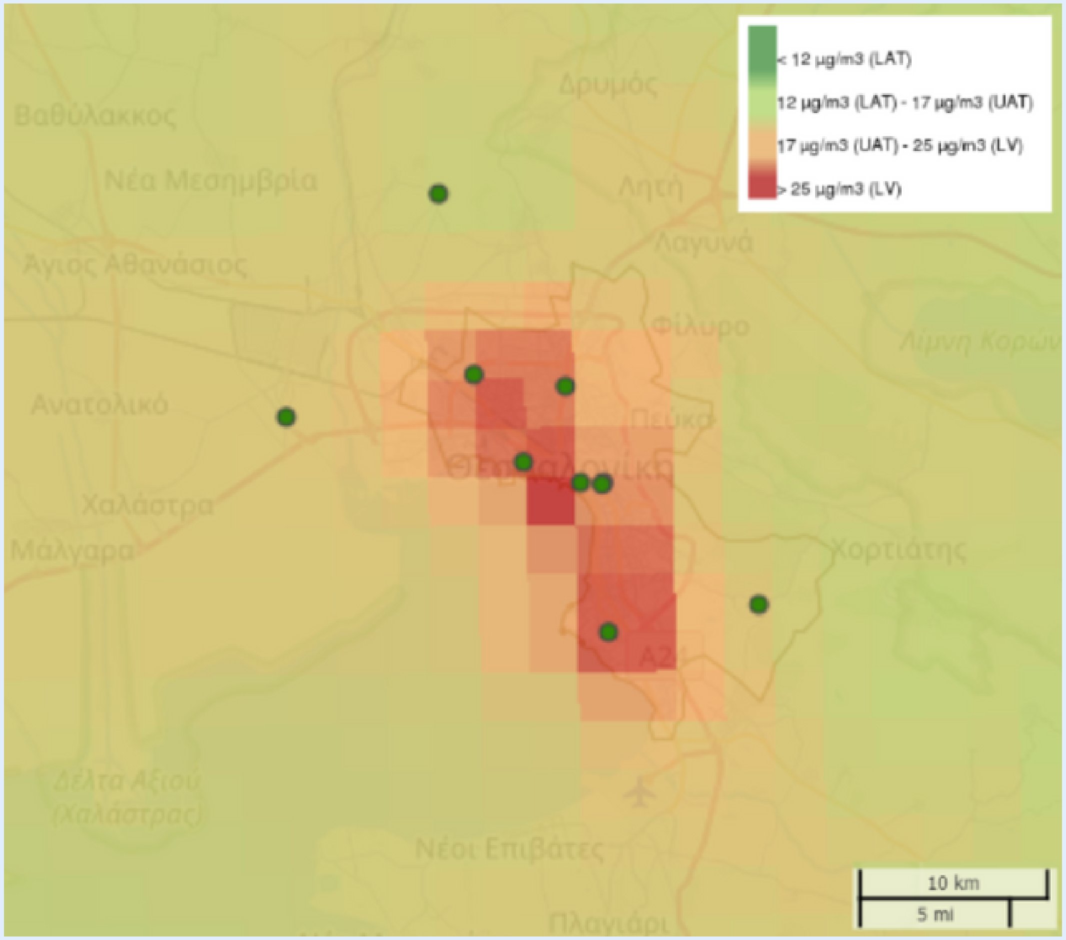

Figure 5: Greek Ministry map of PM concentrations, marked with monitoring stations

Note. from Stefanakis, K. (2019). Air quality - PM. Greek Ministry of Environment and Energy. http://mapsportal.ypen.gr/maps/207

This mapping technique has many limitations. Notably, the resolution is too coarse to provide concentration levels for specific locations. Spatial variation in urban air pollution is an important consideration when mapping pollution levels in an area. A study by the EU-based SAVIAH project has found concentrations of NO_2 on roadways are significantly different from concentrations less than 100 m away from the same roadway (Briggs et al., 1997).

Spatially distinct regions do not experience the same concentrations of pollutants which are generalized by current measurement efforts. Penza (2012), of the ENEA Energy and Sustainable Economic Development in Italy, notes how low-cost and portable sensors allow for much greater temporal and spatial resolution for air pollution studies. Increased monitoring can enable mapping at finer scales of resolution and can be used to evaluate the pollutant concentrations experienced at different locations.

Prior Work in the Thessaloniki Region

The Municipality of Thessaloniki previously partnered with multiple EU-funded projects to address concerns about indoor and outdoor air pollution monitoring. The preliminary involvement plans include AIRTHINGS and LIFE SMART IN'AIR (Papastergios et al., 2019). AIRTHINGS, known also as Fostering resource efficiency and climate change resilience through community-based Air Quality Internet of Things, used 22 air quality sensors that provided real-time data on an Open Data Platform. It planned to use a community-based approach to create a real-time monitoring network in Thessaloniki by allowing a predictive "open data" system for collected data. (Papastergios et al., 2019). The project resulted in the launch of the Balkan-Med Air app which provides visualization of air quality data collected from the sensors, while also providing general information and tips on air pollution (AIRTHINGS Project, 2020).

Focusing on indoor pollution, the Municipality was a partner in the LIFE SMART IN'AIR project, another EU-funded initiative. Full title, "Smart indoor air monitoring network to reduce the impacts of pollutants on environment and health," planned to use micro-analyzers for BTEX and formaldehyde with a smartphone/web-based interface to monitor In Air Quality (IAQ) in a Thessaloniki school. The project aimed to make the data accessible to citizens, describe the associated health impact from the levels being measured, and lead to changes to improve IAQ (Papastergios et al., 2019).

Researchers from the Environmental Informatics Research Group at Aristotle University conducted a project in the Greater Thessaloniki area to assess air quality monitoring. The project, URwatair, utilized a questionnaire for feedback on air pollution concerns and a collaborative messaging platform alongside the use of low-cost sensors with daily report diaries. The diaries were used to organize daily reports which were crucial in associating certain human activity with increased levels of PM along with predefined scenarios for monitoring such as "Commuting," "My Neighbourhood," "Accommodation Space," and "Cooking." The project pointed to several areas of improvement and future direction such as ensuring easy use of AQ devices and well-structured diaries (Kassandros et al., 2021).

The prior work carried out in the region suggests the use of sensors and microanalyzers can provide real-time data and improved awareness of individual exposure. The increased accessibility of data for residents can help inform choices in their daily life that affect the number of pollutants they are exposed to. Kassandros et al. (2021) noted citizens participating in the project were able to see which activities and scenarios in their daily life increased their exposure to PM. Easy-to-use sensors and simple ways to display the data with the associated health impacts can help drive changes for residents.

Gaps and future areas of work mentioned by the URwatair project include measuring pollutants such as NOx, since they were not monitored by the micro-sensors used, and more specific focus on the quantitative data about the pollutant levels measured. The project focused more on qualitative spikes and their association with specific activities, so future work using similar sensors could focus on comparing the levels with existing monitoring stations in Thessaloniki. The researchers recommended a greater network of sensors being implemented at the community level to provide a greater understanding of everyday indoor and outdoor pollution exposure. Since their project only assessed two outdoor scenarios and two indoor scenarios for monitoring, there is potential to expand the scenarios and locations where air pollution is measured.

The American Farm School & Perrotis College

The Perrotis College of Agriculture, Environment & Life Sciences is the higher education division of the American Farm School with Environmental Science as a main area of study (History and Mission, n.d.). Dr. Georgios Fytianos was an Assistant Professor and head of the Department of Environmental Science at Perrotis College. The collaboration of the Air Monitoring IQP Team and Dr. Fytianos provided data collection of PM, CO, SO_2, and NO_2 concentrations using micro-sensors. The project assesses the localized levels of exposure with a specific focus on scenarios related to the activities, and occupations of residents in Thessaloniki.

Approach

The goal of this project was to investigate localized air pollution exposure in Thessaloniki and communicate the personalized results and effects to employees working in different environments.

Due to the health effects of poor air quality, we investigated significant neighborhoods to the lives of Thessaloniki residents including cafés, restaurants, bars, and popular public streets. Our team recorded air pollutant concentrations with portable micro-sensors to fulfill our localized approach.

Objectives

- **Monitor air pollution concentrations using micro-sensors and analyze relevant location characteristics in the context of air quality**
- **Analyze concentration data across various scenarios such as occupations and outdoor areas to investigate the potential pollutant sources and exposure levels**
- **Determine the air pollution concerns of business owners, employees, and health officials through interviews**
- **Provide owners and workers at local restaurants and cafes with general air quality information and recommendations to mitigate pollution exposure in their work environment**

Figure 6. View from the Aliki Perrotis student residence roof facing south over the fields of the American Farm School

Data Collection Strategies

Neighborhoods of Interest

We focused on specific neighborhoods for data collection to address exposure commonly faced by residents of Thessaloniki. Occupational comparisons, for example, were of great interest because of their applicability to workers and residents who spend much of their time in polluted environments. Measuring highly trafficked indoor and outdoor locations within the city would apply to most Thessaloniki residents and their exposure.

We concentrated on cafés and restaurants because they are popular gathering spaces and can expose both workers and customers to air pollution. Neighborhoods of interest to our project include the streets around Nikis and Egnatia, along with the neighborhood of Ano Poli, since they have significant cultural and historical importance to the city's residents. Their locations are depicted in Figure 7.

Nikis is the street adjacent to the waterfront in the center region of downtown, receiving extremely high foot and vehicle traffic. The side of the street towards the city contains many popular restaurants, cafés, bars, and convenience

Figure 7. Areas of interest for data collection

Note.The green lines depict major arterials in downtown Thessaloniki including the streets of Egnatia and Nikis. The blue region encompasses Ano Poli.

stores essential to life in the area. The opposite side along the waterfront is a popular destination for evening walks which are central to Greek culture.

Egnatia is the main arterial of Thessaloniki and is one of the most highly used roads for cars, buses, and motorbikes. As a result, we hypothesized this street would likely contain high pollutant concentrations. The street is also home to many shopping centers, restaurants, and historical landmarks such as the Arch of Galerius.

Ano Poli, the old town of Thessaloniki, sits north of the city and contains much smaller streets with a larger concentration of residential buildings. The area holds historical significance to the city because of its historical monuments and old architecture. This neighborhood provided us with a difference in urban design and reduced traffic which we hypothesized would have an impact on ambient pollutant concentrations.

Site Assessments

To supplement the quantitative data collected from the micro-sensors, the team recorded qualitative data during site assessments. We utilized a Google Form to document information about the location, specific to variables that impact air pollution concentration where we monitored. The form contained fields for inputting the start date and time as well as the end date and time.

The name of the location was recorded, and a general description of the location or area of study was documented for future data analysis while the exact locations were omitted for privacy. We also noted a qualitative description of the weather. Included in the form was a field for any other notable conditions at that location that did not fit in with any previous information collected. A common example was several patrons smoking near the team while monitoring was conducted.

A check box section contained all of the sensors the team used for monitoring. We checked off which specific sensors were used at that specific location. Finally, we included pictures to document where the team placed the sensors and another notes field for final thoughts or issues we experienced during collection. This information was automatically compiled in a Google Sheet for simplified data analysis. The fields from the form is included in Appendix B.

Measurement Strategies

The team measured pollutant concentrations with portable micro-sensors to understand trends throughout Thessaloniki. We conducted data collection using two brands of sensors; Envea Cairsens micro-sensors collected data on harmful gasses such as SO_2, NO_2, and CO. These sensors have high accuracy and were verified to European directive 2008/50/EC standards for indicators (Envea, n.d.). Our two Atmotube PRO micro-sensors measured PM concentrations and verified by the Air Quality Sensor Performance Evaluation Center (Atmotube, n.d.). The accuracy of our sensors was critical, so data did not need to be re-verified for the Envea sensors. The portable size of these sensors enabled us to collect data from a variety of indoor and outdoor locations.

Our team employed a measurement strategy for data collection in restaurants and cafés. Since we had multiple sensors, our team split into two groups, taking two sensors each (NO_2 and PM) to collect data more efficiently. Measurements were taken in seating areas with up to two hours of monitoring time per location, mimicking the time a customer spends during a long stay. Each day of data collection included two cafés and two restaurants, specifically chosen from each of the target areas that included characteristics influential to air quality (e.g. an enclosed porch or a patio with smoking). Data collection was conducted each day in one focus neighborhood at a café from about 10:00 until 12:00, and at a restaurant from about 13:00 to 15:00. This daily process was repeated three times each week, each day in a different neighborhood, for a total of three weeks, and provided us with a wide range of pollutant trends for comparison.

Measurements were also taken in static locations over a longer period, specifically in restaurants, where a sensor was left near the kitchen to measure pollutant concentrations throughout the workday. Sensors were dropped off in the evening and retrieved the following morning.

The data collected during air monitoring was organized and documented in a central directory. All of the unfiltered sensor data was compiled into a single sheet for each study. The Atmotube sensor exported a comma-separated value (CSV) file which was imported to Microsoft Excel for further data analysis. An example of the exported data is shown below.

Table 5. Example of exported data from Atmotube sensor

Timestamp	PM_1	$PM_{2.5}$	PM_{10}	Latitude	Longitude
2/14/2023 10:19	1	2.4	3.5	42.27233887	-71.80548443
2/14/2023 10:18	1.3	2.8	3.8	42.27224731	-71.80554396
2/14/2023 10:17	1	2.2	3.4	42.27233887	-71.80553862

Note. Data was collected on the WPI campus using the Atmotube Pro sensor. All PM measurements are in μg/m³.

Data Visualization

Our team used visualization techniques such as graphing and mapping which help our team, our stakeholders, and future researchers understand the trends of the data we collected. We graphed pollutant concentrations versus time for every location which allowed for visual analysis of large spikes in data that was compared to qualitative observations. We also simultaneously compared values between sensors matching the time stamped values in Microsoft Excel, given as mm/dd/yyyy hh:mm, and the corresponding pollutant concentrations which were given in μg/m³. This was primarily done for comparisons with PM and NO_2, as we had three PM sensors and two NO_2 sensors.

Our team also produced maps to display pollutant levels throughout the neighborhoods of interest. We used data from 2 identical sensors present on a walk and pinpointed the values of pollutant concentrations with the timestamped coordinate locations from the Atmotube mobile application. For each map, a color scale was added to represent concentrations of pollutants, with a darker color meaning higher levels. Unfortunately, this scale is different for each map we made as the scale can't be manually edited. An example of mapped Atmotube sensor data is provided in Figure 8.

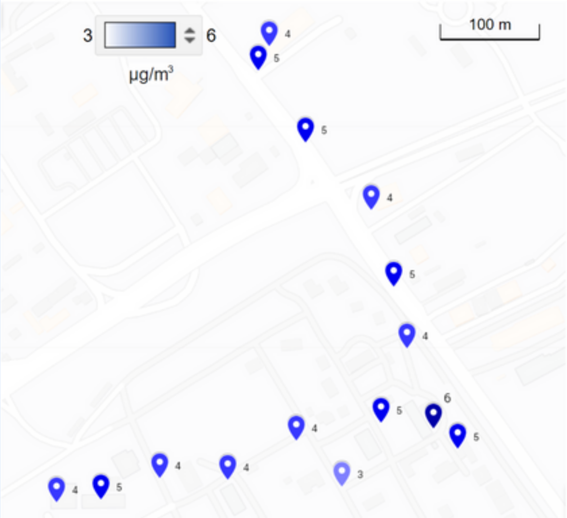

Figure 8. Mapped Atmotube PM_{10} Data

Note. Data was collected on the AFS campus and in the surrounding area between 19:24 and 20:13 on March 28. There was a strong northern wind that day and since the path was very open, we hypothesized that the air circulation contributed to very low PM levels.

Interviews

Stakeholder Perceptions

The collection and analysis of data provided us with experimental results on the actual state of air pollution within our neighborhoods of interest. However, this did not describe how the residents of Thessaloniki perceived their exposure. We conducted semi-structured interviews with business owners or employees to gauge their understanding of air pollution. Our questions investigated their opinions and current knowledge of pollution sources, such as from the kitchen, people smoking outside, and vehicles. This helped guide the creation of our pamphlet that provided general mitigation and information on air pollution. The pamphlet was later brought to seven of the interviewees that were interested in understanding their exposure. The questions we asked in the interviews can be seen in Appendix A. Since these were performed in a semi-structured format, some questions were ommitted and new questions were added to learn more information on a case-by-case basis.

Expert Interview

To gain insight into the perception of air pollution, the current solutions, and how to communicate the risks and mitigation strategies to the public, we interviewed an expert who was a researcher studying ambient air pollution. We interviewed this expert, providing a contrasting perspective from the café and restaurant workers we talked with. The purpose of this interview was to collect in-depth information from an expert which informed the content of our pamphlet and how we would convey the information to local businesses. The interview questions we used are included in Appendix A.

Informing Stakeholders

The team provided key information about air pollution to the business owners we interviewed throughout the Thessaloniki area. This took the form of a pamphlet and contained five main sections. Its purpose was to outline the individualized pollutant exposure, potential sources of pollution, health effects, mitigation techniques, and provide further recommendations or references.

Our first section, pollutant levels, provided business owners with tailored results on pollutant levels in their cafés or restaurants. We used a modification of the Common Air Quality Index (CAQI) to present the air quality with easy-to-understand terminology. The same index and subindex boundaries are used, but we divided the score into a PM and a harmful gasses (NO_2, CO, and SO_2) score to help business owners better narrow down which sources are contributing to the levels of pollution. The next panel of the pamphlet included sources of pollution previously discussed, with information on which sources contribute to which scores. The pamphlet also included a brief section discussing the health effects of air pollution. The neurological, cardiac, and respiratory problems associated with air pollution were included to stress the severity of being exposed to high concentrations of air pollution.

The team provided helpful and relevant techniques to mitigate pollution in restaurants and cafés. These methods included indoor air cleaning systems such as HEPA filters, more enforcement of smoking regulations by businesses, and improved ventilation with increased airflow. We also provided additional references to guide workers toward understanding and improving the air quality. These references included relevant national and international organizations and were improved based on feedback from interviewees on whom they trust for information.

Figure 9. Mark conducting interview

Findings

This chapter discusses our analysis of findings collected through the methodology listed above. Our findings are organized by topic, starting with an analysis of exposure throughout the focus neighborhoods and then a detailed look at pollutant exposure in cafés and restaurants. We contrasted the measured concentrations with the worker's perceptions of air quality to develop pamphlets containing generalized information on air quality. We discuss findings from our return to these restaurants, where we provided personalized air quality scores and additional resources they could turn to for mitigation or more information.

Localized Exposure

***NO_2 concentrations were lower in Ano Poli than downtown, while $PM_{2.5}$ concentrations were similar between neighborhoods*.**

To investigate air pollution exposure at a more localized level, we brought our micro-sensors to three specific neighborhoods of Thessaloniki: Ano Poli, the downtown area of Egnatia, and the waterfront area of Nikis. Our team investigated 36 locations, with 12 in each neighborhood. Because monitoring time varied by location, we only used the last hour of measurements to calculate the average concentration. We organized the hour $PM_{2.5}$ and NO_2 concentration averages by neighborhood in Figure 10 below.

Our team found unsafe levels of $PM_{2.5}$ in all neighborhoods, with 12 occurrences exceeding the WHO 24-hour guidelines. The pattern displayed in Figure 10 shows similar concentrations of PM in each neighborhood. This pattern matches studies that found PM emissions in Thessaloniki are primarily from industrial activity and are distributed with the local circulation of wind (Kassomenos et al., 2011). We also noticed that PM concentrations often correlated with the wind, which seemed to be well-known within the city. Multiple interviewees mentioned how the air is "cleansed by the northern wind." On March 28, our team monitored locations in Ano Poli when the prevailing north wind measured 20-40 km/hour. $PM_{2.5}$ and PM_{10} concentrations recorded this day were four out of the five lowest average concentrations our team measured during the monitoring period.

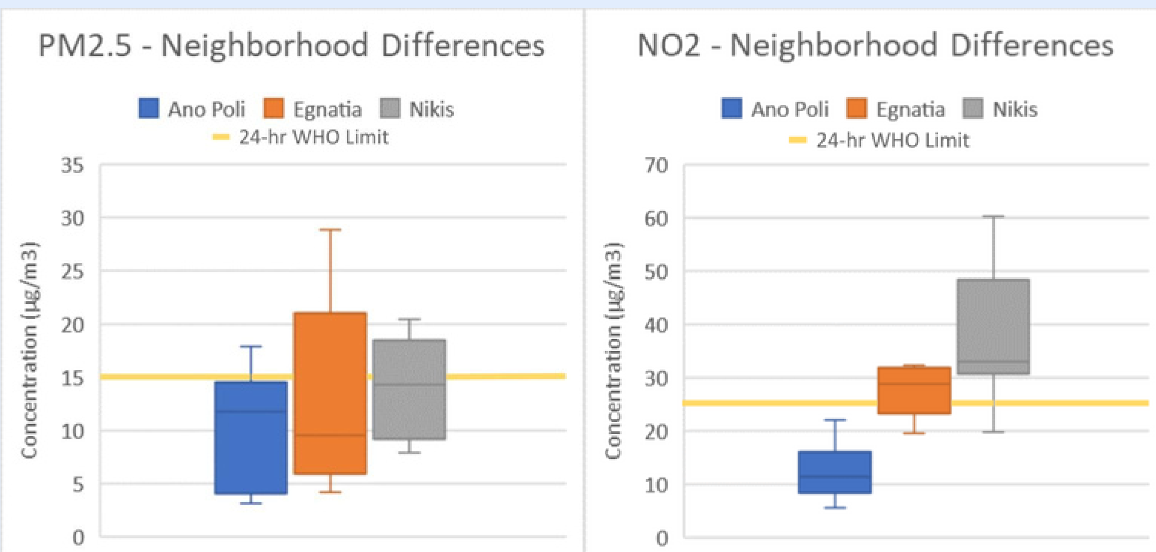

Figure 10. $PM_{2.5}$ and NO_2 concentrations are organized by the neighborhood of focus

Note. 1-hour average concentrations grouped by neighborhood. The box and whisker chart represent quartiles of data we monitored. The line in the center of each bar indicates the median value. For $PM_{2.5}$, 12 data points are included for each focus region. For NO_2, a total of 10 data points are included for each focus region. The significance of these measures and discussion on the 2 outliers for NO2 are present in the following section.

Our team found that concentrations of NO_2 were generally consistent by neighborhood, regardless of the weather and external conditions in Appendix E. The pattern displayed in Figure 10 shows the lowest concentrations in Ano Poli and slightly higher concentrations in Egnatia and Nikis. There is one outlier for each of the Ano Poli and Egnatia datasets. For Ano Poli, we found higher concentrations in a fully-enclosed location with smokers and heat lamps which could have influenced average concentrations. The outlier in Egnatia is notable as it was only a few meters from a busy bus stop. We attribute the larger range of data from Nikis to more local sources, traffic, higher densities of shops and pedestrians, and fluctuations of the wind, as the street runs along the waterfront. The literature generally associates NO_2 emissions with automotive traffic (Valavanidis et al., 2015). Egnatia and Nikis are two of the most congested streets in Thessaloniki; we consistently observed concentrations higher than in a less dense area such as Ano Poli.

Another factor that may contribute to this gradient is elevation. Studies have found that NO_2 concentrations generally decrease as elevation increases (Özden Üzmez, 2018). NO_2 is denser than air and tends to stagnate closer to the ground. Because Thessaloniki is built on a hill as shown in Figure 1, it is expected concentrations would be lower in Ano Poli as it is much higher elevation than other neighborhoods. Nikis and Egnatia are much closer in elevation and experience a similar median concentration. A difference in NO_2 exposure between neighborhoods does have implications. While average Ano Poli concentrations were below WHO thresholds and EU limit values, both Egnatia and Nikis' medians were above the WHO 24-hr guidelines. Sustained exposure at this concentration could lead to health effects discussed previously.

Although we performed most of the data collection at a similar time, mid-day, variables such as weather and time constraints made comparisons between different days problematic. One specific limitation is that we were not able to simultaneously measure pollutants in different locations.

Figure 11. Photo of the sensors we used

Low PM concentrations were found on the streets around Egnatia and Nikis, with smoking causing exceptions.

To obtain more granular data on Thessaloniki's outdoor concentrations, our team investigated several streets around the areas of interest. For the Nikis area, we monitored Nikis, Kilomila, Mitropoleos, and Tsimiski streets, and for the Egnatia area, we monitored Ermou, Svolou, Egnatia, and Filippou. The resulting PM_{10} concentration density maps were compiled into the figures below:

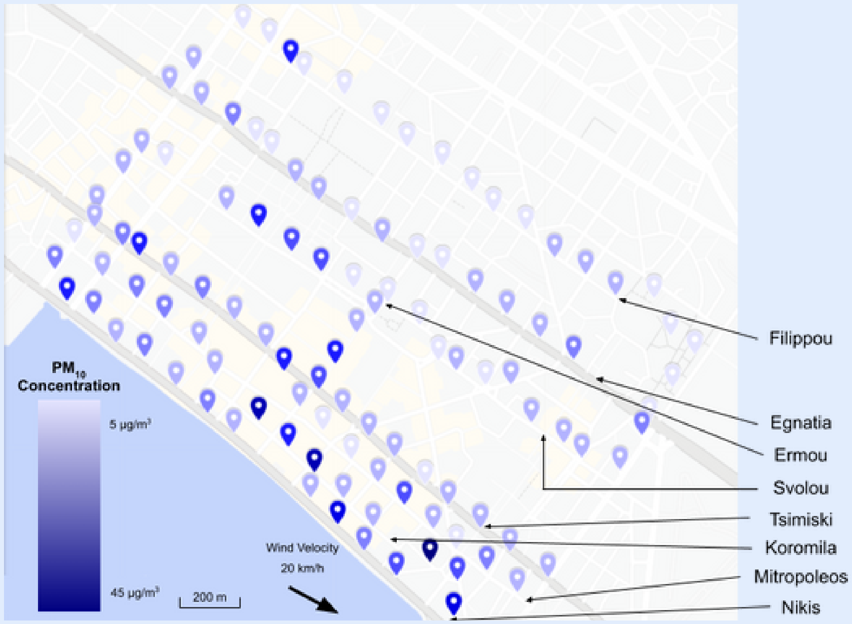

Figure 12. PM walking data of the Egnatia and Nikis areas on April 5.

Note. The walk took place in the afternoon when it was mostly sunny with a light, chilly breeze. We observed several smokers in the Nikis area for this day as well. The 24-hour WHO guideline for PM_{10} is 45 µg/m³.

Figure 13. PM walking data of the Nikis area on March 24.

Note. The walk took place in the late morning when it was mostly sunny with a constant, light sea breeze. The averages on these streets were the highest ever recorded. The 24-hour WHO guideline for PM_{10} is 45 µg/m³.

We discovered that most measured PM_{10} concentrations were lower than the WHO 24-hour guideline of 45 µg/m³. The average concentration density for PM_{10} on every street we monitored on April 5 (Figure 12) was less than 10 µg/m³. We observed dozens of smokers outside at cafés and restaurants when we walked along Mitropoleos, Kilomila, and Nikis. We had the Atmotube application open on our phones and noticed that the spikes occurred close to smokers. Similar results can be seen in Figure 25 of Appendix D which presents our walking data from April 4.

To calculate street averages, the mean was taken of all data points on the specific streets of interest. While other streets had average PM_{10} concentrations of less than 10 $\mu g/m^3$, the March 24 averages for Nikis, Koromila, and Mitropoleos were 34.9, 28.3, and 28.4, in $\mu g/m^3$ respectively. March 24 was an outlier in terms of overall concentration data for outdoors with the most notable factor on this day being the wind pattern. Normally, breezes originated from the north or northwest, as in Figure 12, where air quality was often below EU and WHO standards. However, in Figure 13, a weaker, southwestern wind was present when outdoor PM_{10} levels in the Nikis area were the highest we recorded.

While we utilized NO_2 sensors during data collection, multiple days of measurements were lost due to human error. This affected our ability to have a complete dataset for comparing concentrations at simultaneous locations. The mobile NO_2 data was also unrecoverable, therefore we could not create concentration maps as seen in Figure 12 for PM.

Other Observations

PM concentrations were similar at street level and on a balcony.

Another monitoring scenario investigated in the city center was the differences in PM concentrations between a bench at a busy intersection and an 8th-floor balcony. One Atmotube sensor was placed on a sidewalk bench across from the building's entrance, and the other sensor was used to monitor from the 8th-floor balcony, overlooking the street. The concurrent monitoring resulted in average $PM_{2.5}$ and PM_{10} concentrations with a difference of less than 2 $\mu g/m^3$ based on an hourly reading. The only notable qualitative difference between the two locations was a person vaping on the sidewalk bench near the sensor. We observed more spikes in PM concentrations for the entrance level which aligns with our finding of increases in PM around smokers. However, the overall difference between the two settings was small enough to not warrant further investigation.

Average NO2 levels were below the WHO threshold for the AFS guards.

We examined pollutant exposure for another occupation, guards at the front gate of the AFS, by collecting measurements of PM and NO_2 on campus. The intent was to observe the pollution exposure at the gate where security guards work and compare the concentrations to an area on campus away from the gate. This comparison was to see if guards were potentially exposed to harmful levels of pollutants from traffic especially during peak hours, 8:00-9:00 and 14:00-16:00. PM and NO_2 sensors were left at the front gate and open-air sitting areas along the Olive Trail from the morning to afternoon pick-up times for the lower schools. The Envea PM and NO_2 sensors measured levels at the gate while the Atmotube PM and Envea NO_2 were at the Olive Trail over two days. Due to the sensor availability, we were not able to use the Atmotubes simultaneously, and we did not have a second sensor for any of the other

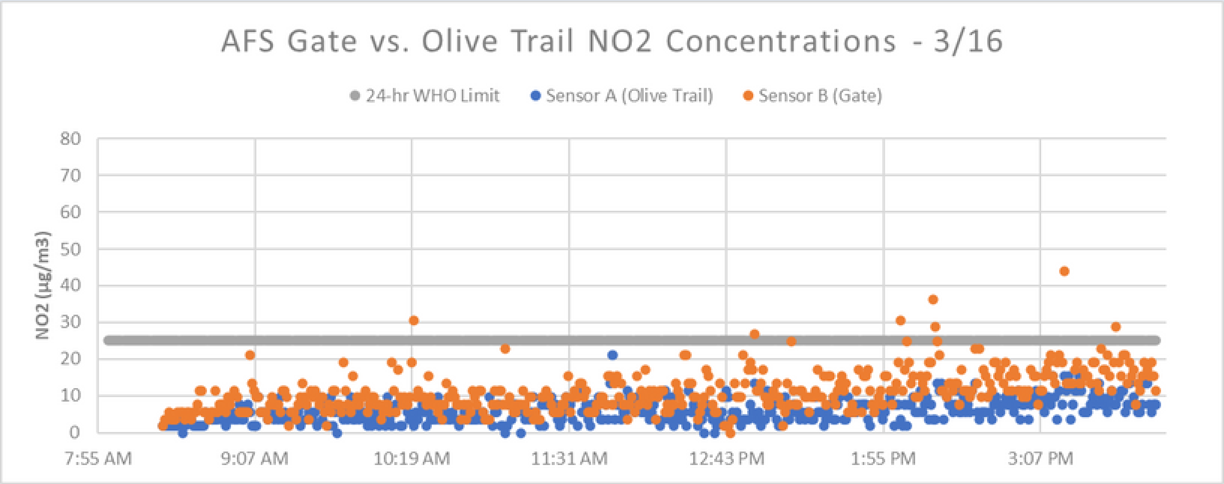

Figure 14. AFS gate vs. Olive Trail NO_2 concentrations on March 16

Note. NO2 data was collected on March 16 using Envea Cairsens Sensors. Sensor A was located on Olive Trail benches in the center of the AFS campus. Sensor B was located at the AFS Gate.

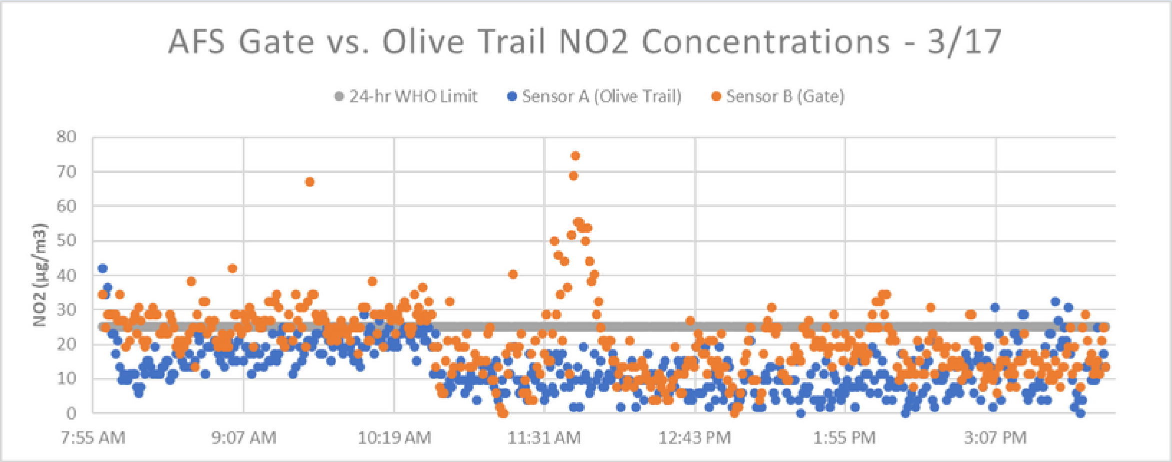

Figure 15. AFS gate vs. Olive Trail NO2 concentrations on March 17

Note. NO2 data was collected on March 17 using Envea Cairsens Sensors. Sensor A was located on Olive Trail benches in the center of the AFS campus. Sensor B was located at the AFS Gate.

pollutants. The PM data was determined to be unusable due to sensor malfunction. The $PM_{2.5}$ values were higher than PM_{10} which is not possible since PM_{10} is made up of particles ≤ 10 μg/m^3.

The NO_2 data observed in Figures 14 and 15 display that the concentration was higher at the gate than at the Olive Trail benches on both days of monitoring. The average concentration for March 16 was 5.98 vs. 10.98 μg/m^3 for the Olive Trail compared to the gate. Similarly, on March 17, the average concentrations were 12.97 and 20.60 μg/m^3 respectively. The sensors on the second day had to be removed earlier than the first collection because it started to rain, and they are not waterproof. It is also important to note that on March 17, there was a transportation strike that caused limited buses and taxis to be running. The NO2 readings may have been affected by the lack of buses and taxis and the increase of cars on the road. None of the average concentrations for gate or Olive Trail exceeded the 24-hour WHO guidelines. We observed more exceedances above the limit for March 17, but the overall average is not considered harmful. This suggests exposure levels over shorter periods do not indicate health risks to guards, however extended monitoring is needed to determine possible long-term health effects.

Exposure and Perceptions of Stakeholders

Passive smoking was the preponderant source of air pollution exposure to café and restaurant customers, with no correlation to differing settings.

We characterized 36 data collection sites by their surroundings noted in our site assessments into the four following categories.

1. Fully-enclosed outdoor areas: outside a building, only open to the air on one side or less, with other sides normally being flexible clear plastic.
2. Semi-enclosed outdoor areas: similar as prior, except at least two or more sides open air.
3. Outdoor areas: open to the air on all sides, e.g. on sidewalks in front of a building.
4. Indoor areas: fully within a building, with little to no openings outside.

Examples of these categories are shown for reference in Figure 16.

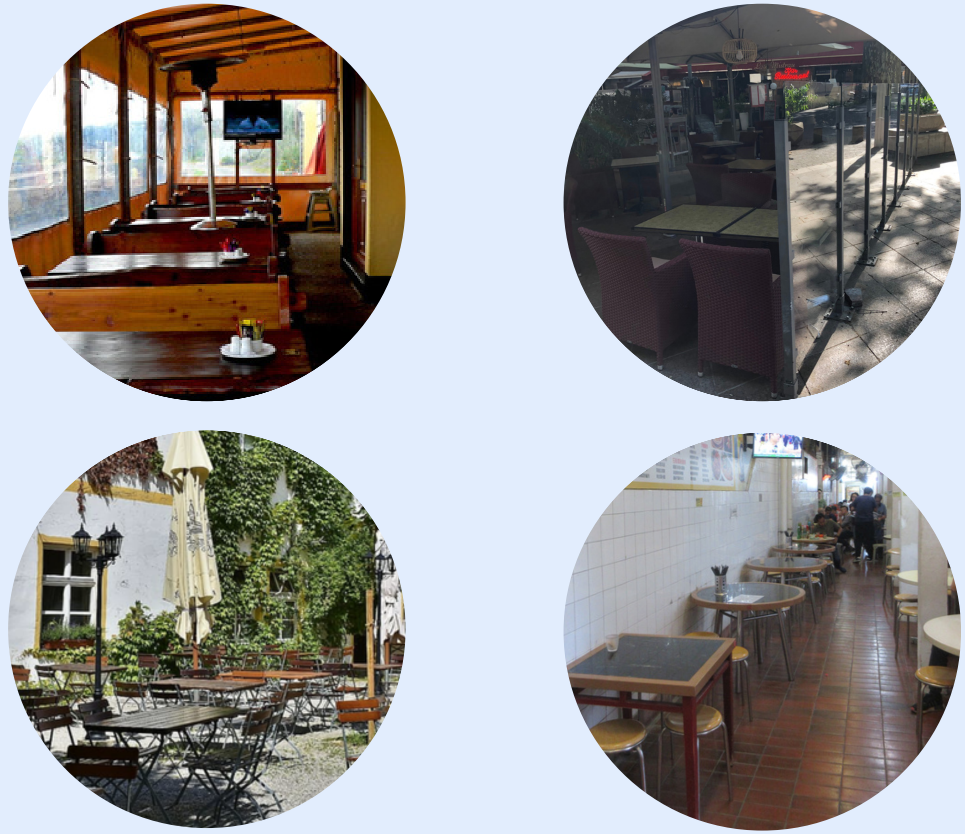

Figure 16. Examples of monitoring location categories

Note. Top left, fully-enclosed outdoor. Top right, semi-enclosed outdoor. Bottom left, outdoors. Bottom right, indoors. Photos are not of monitoring locations to preserve anonymity. From:
Mischyshyn, J. (2012). *Enclosed Area at Front.* [Photograph]. https://www.geograph.ie/photo/3055929. (CC BY-SA 2.0).
Mistrau, L. (2022). *Outdoor seating.* [Photograph]. https://commons.m.wikimedia.org/wiki/File:Outdoor_seating,_Lou_Mistrau,_pl_Horloge,_Avignon_-_2022-06-03.jpg. (CC BY-SA 4.0).
Pxfuel. (n.d.). *Fold umbrella, set, house, Beer Garden, Chairs, Dining, Tables, dining tables, summer.* https://www.pxfuel.com/en/free-photo-ogwff. (Public Domain Certification)
Lainm, M. (2018). *Indoor market cooked food restaurant tables and chairs.* https://commons.wikimedia.org/wiki/File:HK_%E8%A7%80%E5%A1%98_Kwun_Tong_%E9%A7%BF%E6%A5%AD%E8%A1%97_Tsun_Yip_Street_indoor_Market_cooked_food_restaurant_tables_and_chairs_October_2018_IX2_01.jpg. (CC BY-SA 4.0).

Figure 17 compares the average concentration of each pollutant across all cafés and restaurants we monitored during the three weeks (March 24 - April 11, 2023) at each setting. We expected more enclosed outdoor areas to retain all pollutants at higher rates than open outdoor areas due to interior sources, such as smoking, being trapped. Based on the literature in the background, SO_2 is expected to have higher concentrations outside since the most common source is inefficient combustion from vehicles. CO is most likely to be highest indoors because it comes from indoor appliances that run on natural gas while having less room to disperse.

The results indicate no correlation between setting characteristics with both PM and NO_2 average concentrations. However, these graphs depict similar patterns, with outdoor and fully-enclosed outdoor areas having the highest levels, while indoor and semi-enclosed outdoor areas are consistently the lowest. SO_2 concentrations were highest in the most exposed settings such as outdoors, followed by semi-enclosed outdoors. CO concentrations were over three times greater indoors compared to the three types of outdoor settings.

We were limited by the size of our data set for different settings because we prioritized measuring 12 locations in each of the three

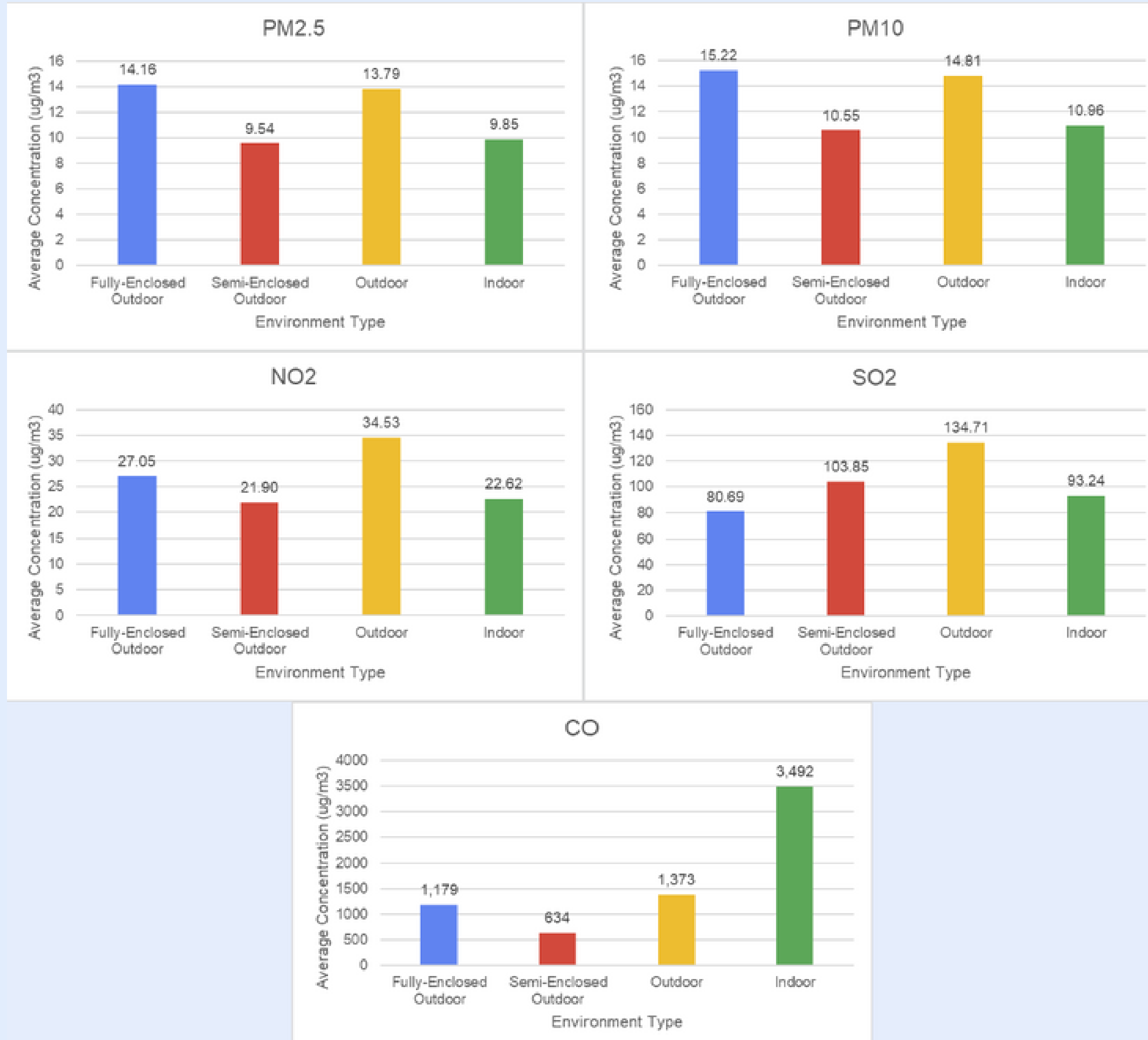

Figure 17. Comparison of average pollutant concentration versus setting type

Note: Trends of SO_2 and CO match expectations. PM and NO_2 indicate no discernible difference between indoor and outdoor locations.

neighborhoods. This, coupled with the variable availability of both indoor and outdoor seating at cafés or restaurants, created an unequal distribution of what settings we could monitor. Our data had a larger bias toward outdoor seating locations which were more common in the neighborhoods we studied.

Since we collected data during the months of March and April, most locations in our areas of interest had neither heaters nor air conditioners operating, which are primary sources of pollution identified in previous chapters. These results are limited in their applicability to customers since these locations are not busy during the typical mid-day monitoring period. Our team decided against switching the monitoring period to a busier time due to our short study duration. The micro-sensors are not waterproof, thus limiting our collection to indoors on days with precipitation and overall limiting the opportunities to collect data.

During our experiences collecting data, we noticed that while PM levels, in general, were below limits, they spiked when people sitting near the monitors were smoking or vaping. An example of this can be seen in Figure 18 which displays a whole day of data collection with PM concentrations. In the figure, there are evident but sporadic increases in PM levels when between 10:00-11:00. In our qualitative forms, we noted that at this time, smokers were sitting very close and their smoke was blowing toward our table. This same trend occurred at almost every single café we visited throughout our three weeks of monitoring.

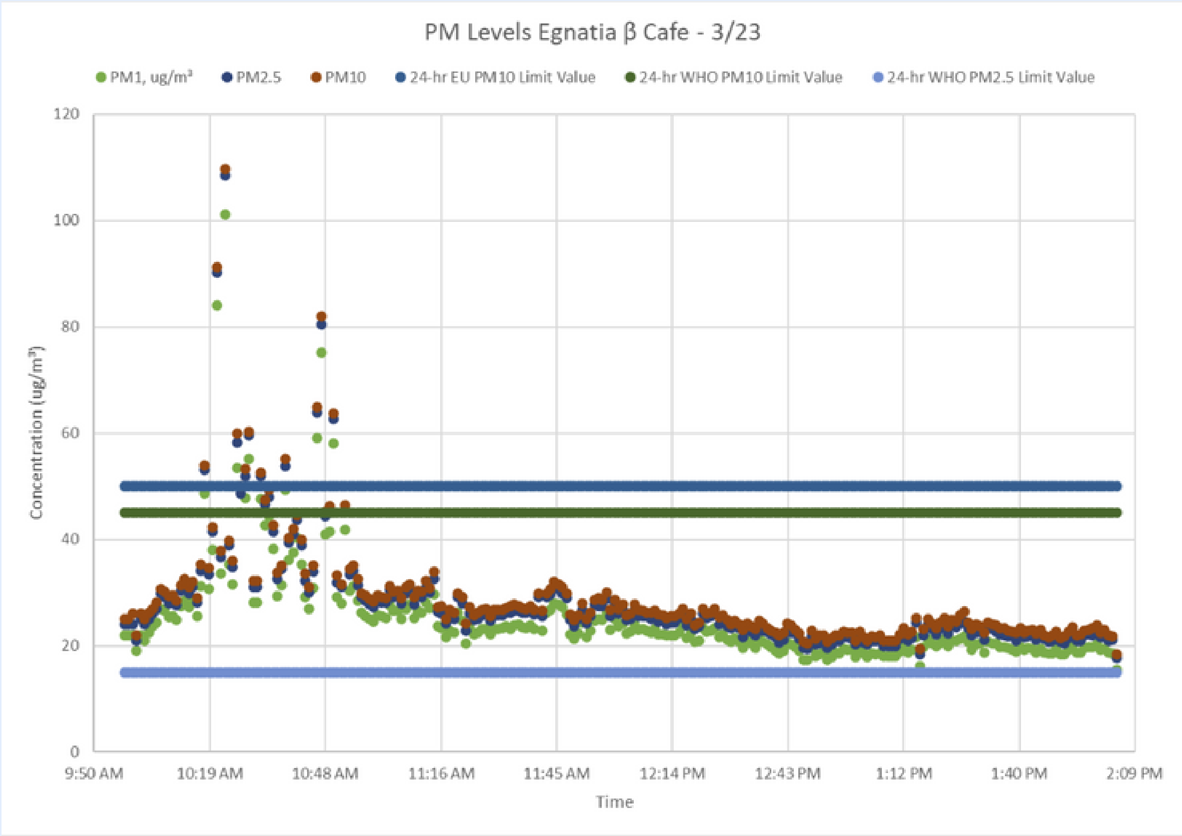

Figure 18. PM concentrations on March 23 of data collection on Egnatia

Note. Smokers were present for a 1-hour duration at a café beginning at 10:00.

Restaurant Employees experience concentrations of PM consistently around and above WHO guidelines.

We conducted two in-depth comparative studies between the exposure of staff and customers, focusing on the bar and kitchen areas of restaurants. We monitored PM levels for two evenings to better understand the extent to which waiters and kitchen staff were exposed to pollutants from cooking during busy periods. Only one PM sensor was used due to limited availability for our study.

Restaurant 1 was located on a small side street near the city center. Notable conditions for reducing air pollution exposure was the restaurant's ventilation system which consisted of extensive ductwork and a vacuum fume hood above the kitchen. For this study, the Envea PM sensor was used and placed above the bar area which is adjacent to the kitchen and dining room. Data was collected for as long as the external battery lasted which was from March 23 at 20:00 until March 25 at 4:30.

The results reveal spikes in PM concentrations at similar times on different days. In a follow-up interview, we asked the owner to consider what events might have caused the spikes we saw in the dataset. Figure 19 below depicts the concentration of $PM_{2.5}$ from each day overlaid using a 24-hour scale on the horizontal axis to align changes with specific daily actions. $PM_{2.5}$ was analyzed because it was the most prominent of the PM type, similar trends were seen in PM_{10} and PM_1. The first and largest spike occurred around 1:30 in the morning (after the customers had left) and coincided with the time the restaurant staff turned off the ventilation system and began smoking indoors. A second spike occurred between 7:00-8:00 when the kitchen opens in the morning and cooking appliances are turned on. Small sudden increases appear during the day with no known correlating causes. A final spike occurred between the hours of 20:00-22:00 which was recorded as the busiest time in the restaurant. The 24-hour $PM_{2.5}$ limit described by the WHO is included on the graph to illustrate the levels are constantly above the safety guidelines.

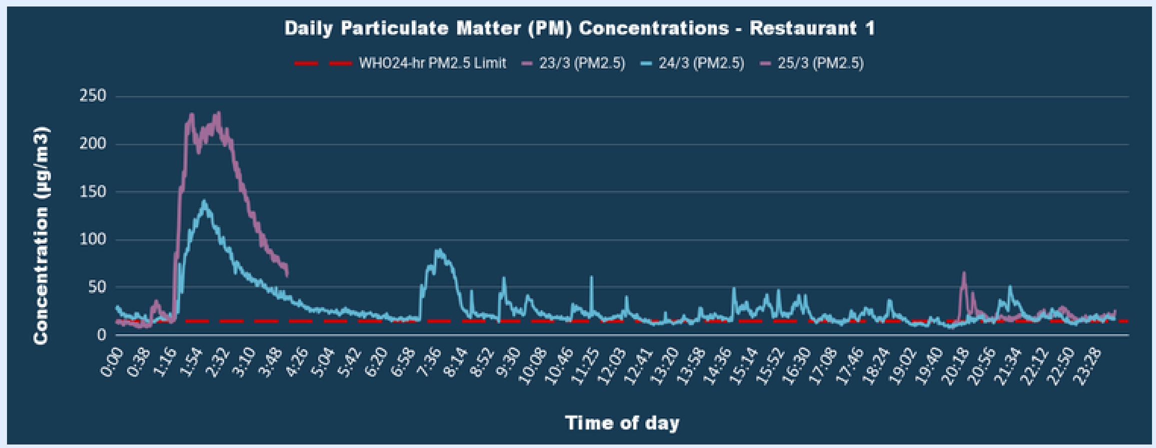

Figure 19. The concentration of $PM_{2.5}$ versus time of day at restaurant 1

Note. Significant spikes indicate dangerous levels of PM are present, however, the concentration always is above recommended WHO guidelines.

Restaurant 2 was located just southeast of downtown on a moderately busy street. We collected data on the upstairs floor which had only one open entrance. An Atmotube PM sensor was placed on shelves at the edge of the bar closest to the kitchen. Data collection lasted for a complete day. Results display $PM_{2.5}$ concentrations consistently above the 24-hour WHO guidelines, illustrated in Figure 20. PM_{10} concentrations mostly did not exceed EU and WHO guidelines but spiked on six separate occasions. The spikes between 0:00 and 3:00 were likely due to the large number of customers in the bar, with PM coming from people smoking outside or cooking in the kitchen. The last sudden change in pollutant concentration around 14:00 aligns with the start of food preparation in the afternoon. However, we were unable to follow up with the owner to confirm these hypotheses.

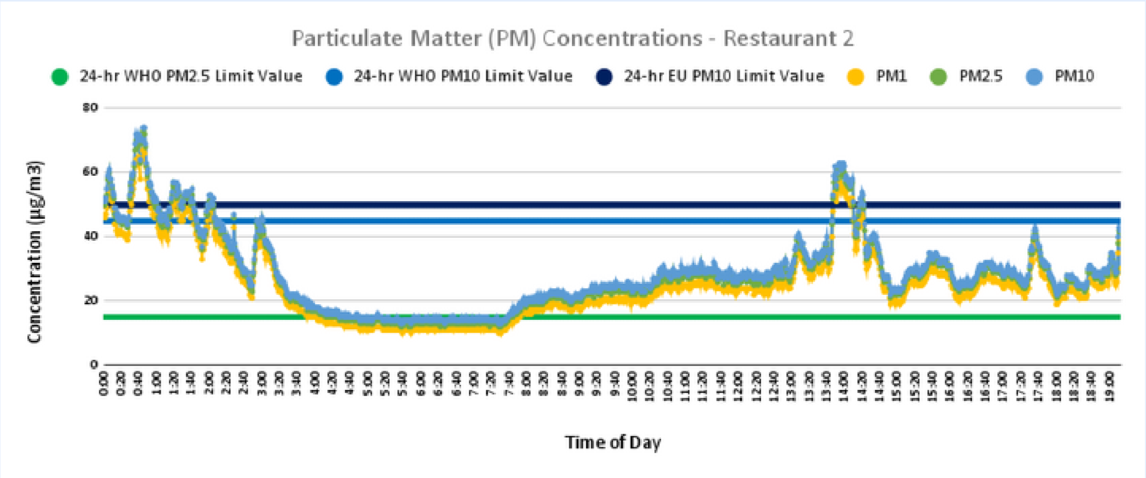

Figure 20. The concentration of PM versus time of day at restaurant 2

Note. Significant spikes indicate high levels of PM are present. PM_{10} concentrations occasionally rise above the WHO and EU-regulated limits while $PM_{2.5}$ is consistently above the WHO guidelines.

We discovered stakeholders have a lack of prior knowledge but a desire to learn more about air quality.

Our team conducted nine interviews over the three weeks of data collection. Eight of these were with employees at the cafés or restaurants we monitored, while only one interviewee was a manager. We aimed to learn general information about the time they spend in the environment and identify any source that reduces air quality. Our team prioritized questioning whom interviewees would trust to learn what information would be most helpful. After initial observations revealed the prominent effect of smoking, we asked stakeholders if they had noticed changes to indoor air quality after the 2010 smoking ban. As a result, we can compare this perceived exposure to the air quality data gathered at the same location. The interviewees and their responses are summarized in the Table 6.

Many of the café and restaurant workers we interviewed had limited knowledge of the sources, did not think they could take action to improve air quality, and did not know whom to get reliable information from on air pollution exposure or health risks. Those who indicated sources they trust mentioned the opinions of academic researchers from local

Table 6. The key information we gained through interviews with café and restaurant workers.

Interviewee Number	Role	Who They Trust	Other Key Responses
1	Employee	Only academic sources.Does not trust the government, news, or social media.	Indoor air pollution improved after smoking ban, believes pollution comes from the west side of the city, lifestyle changes have no effect on air pollution
2	Employee	Trusts researchers for reliable information	Assumed good indoor air quality in café, thinks they cannot influence air quality
3	Waitress	Does not know who to trust	They can feel the air pollution on weekends from traffic, they would consider getting an air purifier but nothing else
4	Waiter	N/A*	The business would not consider spending money on anything other than food, huge positive difference in indoor air quality since smoking ban has been in place
5**	Employee	Would trust representatives of the Municipality or State.	Air quality was bad from nearby street, could feel the fumes as buses go by, owner would not be willing to make changes for air quality
6	Employee	Not sure where to get reliable air quality information	Considered air quality to be good inside due to ventilation system, does not believe restaurant would make changes to improve the air quality
7	Waiter	Trusts academic researchers the most	Restaurant is family owned and run, not willing to change habits to improve air quality, notices big improvement in air quality without smokers present
8	Employee	N/A*	Air quality is normally bad due to traffic
9	Manager	Unsure of who to get reliable information from	Air quality is good inside the café, could be better in the city, smoking was prohibited indoors before smoking ban

* Language barrier prevented common understanding
** Interview was live translated by our Greek coresearcher
Note. Names and specific locations are absent to protect the anonymity of businesses.

universities and the government. One exception, interviewee 1, did not trust the government or social media at all for information and only trusted academic researchers.

Overall, we observed our stakeholders were unaware of their exposure to air pollution. When shown the current monitoring data provided to residents, the IQAir real-time air quality platform, café, and restaurant workers said they had never seen or known of the system before.

All the interviewees were interested to learn about their exposure and for us to return with more information. We gained key insights after returning to these places with more specific directions on air quality statistics which is discussed in the next section. However, we learned that some managers or business owners would not spend money to implement or upgrade systems for the sole reason of improving air quality.

According to prior results, the highest concentrations of PM stem from passive smoking, specifically inhaling secondhand smoke, rather than larger sources such as traffic. Some interviewees were aware of the danger smoking presented; however, most assumed worse air quality was attributed to either traffic or industry. Over half of the interviewees also noted that they believed they could not impact the air quality by acting themselves.

Communicating Air Quality to Stakeholders

We discovered a need to appropriately present information on air quality to stakeholders.

Restaurant Owner 1 was interested in learning more about the pollution levels in his establishment, understanding the data, and considering how he could make changes in the restaurant to mitigate potential high levels. We developed a tri-fold pamphlet, "A Quick Guide to Air Quality," to provide information on these topics. Riley et al. (2021) describe how technological solutions are insufficient and engagement with the public is an effective way to target human behavior that contributes to air pollution exposure and concentrations. We used other principles from the literature including the use of actionable information and involving smartphones. Our suggestions on how to improve air quality provided feasible ways stakeholders can make changes. The literature suggests providing actionable recommendations can help with feelings of powerlessness by offering solutions they can implement (Riley et al., 2021).

The first draft of the pamphlet was initially based on background guidance from our "Health of Air Pollution" chapter and structured based on the initial conversation with Restaurant Owner 1. The main panels included information on the types of pollutants studied, their sources, the health effects of air pollution, how to improve air quality, and additional references. A challenge was to focus on information that was most crucial and impactful but fit best in a pamphlet format.

We further tailored the content based on the perceptions and opinions of owners and employees to effectively communicate the scientific information to them. This helped narrow down what information was most beneficial for stakeholders. The responses from interviewees aligned with the literature on science communication of air pollution where local government and researchers were the preferred source for information (Pfleger et al., 2023). We included logos from Perrotis College and WPI on the cover to establish the trust of academic researchers. However, one interviewee was an outlier in not trusting the government which led us to provide a non-governmental resource, the IQAir website on regional air quality in Thessaloniki.

We addressed the view that owners would not be willing to make changes by providing low-cost and feasible ways to improve air quality. These suggestions such as opening a window or not allowing smoking in enclosed spaces are also simple ways employees could take action. We provided more extensive suggestions such as ventilation systems and air filters for the few owners that were more open to feedback.

We found using air quality scores and simplified language to be effective in communicating about pollution.

After creating the first version, we revisited Restaurant Owner 1 with our pamphlet to present the data from their restaurant for feedback. The overall response was positive while providing constructive comments on areas of confusion. He found the sources of pollution helpful since he was not aware that kitchen appliances were a source, and he was interested in implementing ways to improve air quality. The QR codes to other references were also useful in providing further material. The codes are on the back panel of the pamphlet to direct stakeholders to where they can learn more about topics discussed in our pamphlet. They were scannable by a smartphone camera and could direct users to information from live air quality monitoring for Thessaloniki, the World Health Organization, and European Environmental Agency.

Restaurant Owner 1 did not understand what the pollutants were and which were the most prominent in the restaurant. This is likely because the original pamphlet lacked descriptions of the pollutants. The data we collected was only PM and not CO, SO_2, or NO2, but our pamphlet mentioned all the pollutants, leading the owner to believe we measured them all. This led to several adjustments such as categorizing CO, SO, and NO2 as “Harmful Gasses” for readability and an easier way to express AQI scores. We realized it would be too cluttered to include each pollutant we measured at that location and their scores. Therefore, we used the Common Air Quality Index (CAQI) to characterize the two pollutant categories with an area for other notes. A description of “Harmful Gasses” and “Particulate Matter” was also added before the pollutants section. This also aligns with other feedback from an expert in the field who recommended information from Kassomenos et al. (2011). The study recommends air quality indices as the ideal way to represent air quality and is understandable for the public. Other suggestions from our advisors included removing the outdoor heaters as a pollution source and making smoking a more prominent feature based on our monitoring observations.

A challenge we previously mentioned was the language barrier and syntax differences with certain interviewees not understanding the wording of our questions or the questions not coming across the way they were intended. When our co-researcher was available to join our interviews, he helped clear up confusion and put interviewees at ease when they could ask him for clarification in Greek. This also would be beneficial in establishing more trust between us as researchers working directly with Greek researchers and the interviewees. This language difference was reflected in the English version of the pamphlet when describing smoking as a source. Originally, smoking was the only word used to describe the smoke released into the air when a person exhales. The descriptor was pointed out by an advisor as being too vague and changed to “second-hand smoke.” After speaking with our Greek co-researcher and sponsor, they suggested using “passive smoking” since this is a phrase used more commonly among native-Greek speakers in English. Using mechanical translation and refinement from our collaborators, we produced a Greek-language version of the pamphlet since most interviewees were more fluent in Greek than English. The pamphlet in English and Greek can be found in Appendix C.

Feedback from interviewees provided insight into the importance of publicizing the impact of air pollution.

Our team successfully distributed seven personalized pamphlets and conducted follow-up conversations with five workers about the individualized pamphlet for their workplace. We found most were not surprised about their workplace’s AQI score. Only Interviewee 9 expected lower air quality than the actual score. When they were shown the recommendations panel, employees confirmed they already did not allow smoking inside and two of the employees were interested in investing in some of our other suggestions. Another section we referred to was the references panel where we showed them the IQAir website. None had seen this website or an air quality map before; in addition, two interviewees thought our pamphlets were more helpful than looking at the website. The Greek version of the pamphlet reduced language barriers with most interviewees, but there was residual miscommunication for those with limited English fluency.

The most impactful reactions were from three employees shocked by the health effects, commenting on mortality, and expressing sadness. This confirmed our view that emphasizing the health effects draws attention to how serious of a matter air pollution is. The inaccessibility of air quality scores online may be rectified by raising awareness of where to find the data. There is a lack of awareness about current mortality and morbidity rates due to air pollution, as well as the health effects with increased risks.

The feedback from Interviewee 7 was the most insightful, as he described his perspective on the indoor smoking ban. He worked at a restaurant with a rooftop area, covered by a tent, which allows smoking when plastic panels are removed. At the time of the interview, it was fully enclosed and smoking was not allowed. This employee explained that despite knowing about the dangers of smoking, it is a large part of Greek culture. He commented that it is still very difficult to tell people not to smoke in enclosed spaces, and customers will leave non-smoking cafés and restaurants to find places that allow smoking. This indicates there are social pressures on businesses to allow smoking to retain customers. We were surprised to learn about the challenges café and restaurant owners face to accommodate smokers.

The greatest challenge we found when distributing the pamphlets was not following up with the original people we interviewed. Approaching a different employee limited the ability to compare initial responses with this follow-up conversation; it also limited the chances that they would be willing to discuss their workplace's air quality. One attempt to receive feedback resulted in some of our team being turned away from an establishment by a manager unwilling to discuss air quality. However, at one café, we were able to find the owner instead of the original employee. This prompted a more detailed discussion of his business practices for mitigation.

Monitoring Challenges

Our team faced challenges with sensor performance due to measurement inaccuracies.

The Envea PM sensor conformed to European directive 2008/50/EC standards for indicators, so we assumed it was reliable. The Atmotube sensors are verified by Air Quality Sensor Performance Evaluation Center (AQ-SPEC), however, they do not follow European directives. To validate the measurements of the Atmotube sensor, our team compared it to the verified Envea PM sensor. Our team ran the sensors simultaneously in the same location. for 1 hour. The sensors proved to be similar with Atmotube concentrations being within ±2 μg/m^3 for each of PM_1, $PM_{2.5}$, and PM_{10} of the Envea Sensor. This test was limited to stable indoor conditions at low concentrations <15 μg/m^3 with no notable spikes in PM.

During the monitoring period, it was observed that the Atmotube sensors provide a similar difference of PM_{10} to $PM_{2.5}$ regardless of concentration. PM_{10} refers to any particle below 10 μg/m^3 and includes $PM_{2.5}$ and PM_1. A larger ratio of $PM_{2.5}/PM_{10}$ implies the makeup of $PM_{2.5}$ in the air is substantial with almost no PM_{10}. The average ratio throughout our monitoring period was 0.9, with some minute measurements at high concentrations exceeding a ratio of 0.98. A study in the UK involving 46 different monitoring stations presented "five years minimum, median and maximum PM/PM_{10} ratios were 0.40, 0.65 and 0.80, respectively" (Munir, 2017). With our measurements greatly exceeding this range, some potential explanations for this difference would be a different environment, resulting in different ratios of PM, or sensor inaccuracies affecting measurements. Further testing and comparisons using a validated sensor are necessary to confirm whether the data is accurate.

Conclusion

Recommendations

Investigate areas for future research.

We recommend a more in-depth study be taken into each of the facets we explored. Ideally, these studies would be conducted over a longer period, on the scale of five to six months, to account for seasonal variations. When investigating cafés and restaurants, monitoring times should be during busier hours, around 13:00-16:00 and 20:00-22:00, respectively. The substantial amount of data gathered from such a large data set would eliminate any risk of outliers and be more comparable to EU or WHO annual targets. A stricter methodology with isolated variables such as setting or location would improve findings to a point where solid correlations could be found. Examples of these studies are provided in Figure 22 on the next page.

Figure 21. Aliki Perroti Educational Center Entrance

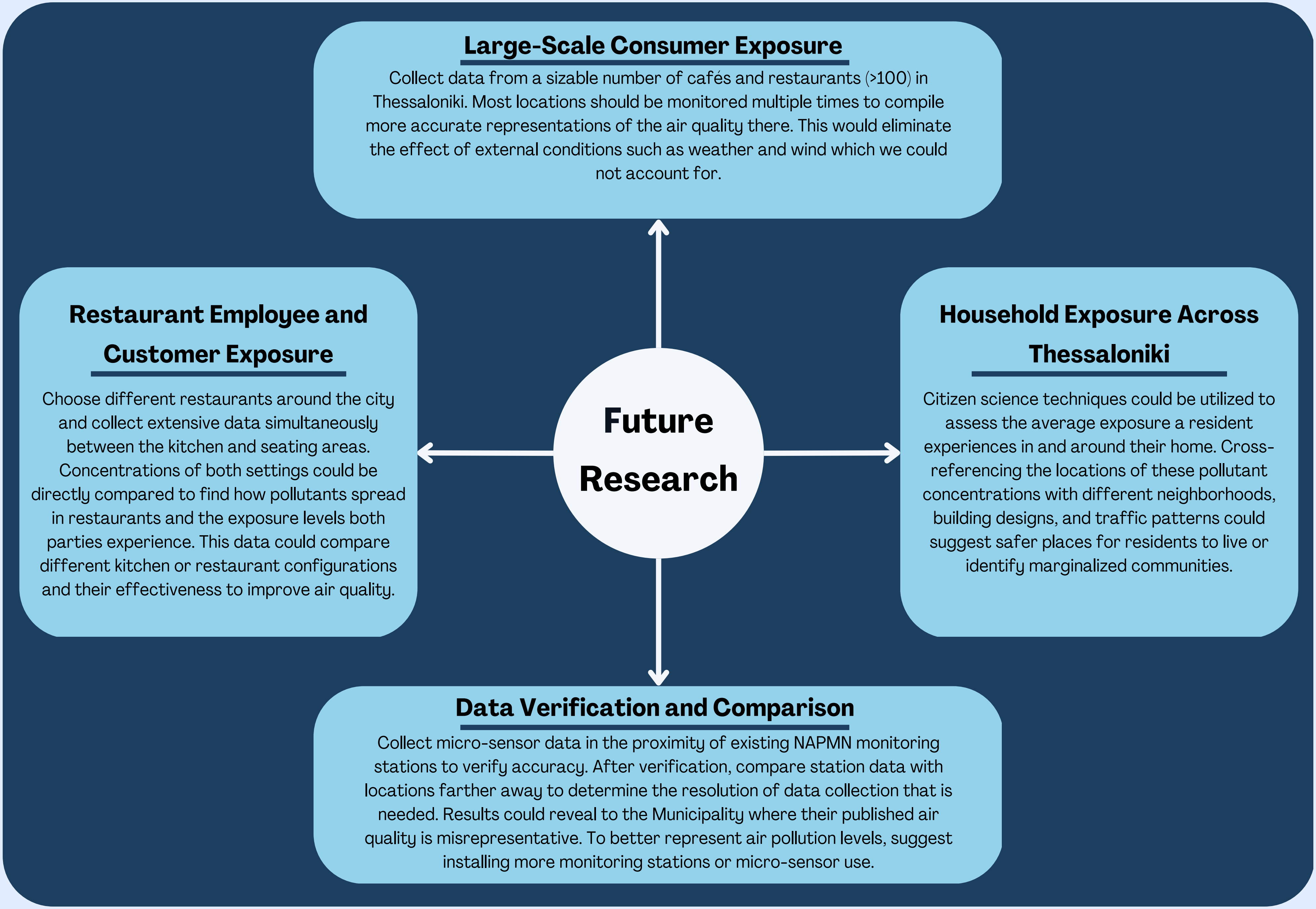

Figure 22. Diagram containing four different areas for future research

Perform a more in-depth study focusing on emissions and external contributions to ambient concentration levels.

We believe that further investigating the factors of air pollution will provide a better understanding of the concentration levels we measure. In our initial research, our team found that industrial emissions, residential heating, and transportation emissions were the main sources of air pollution in Thessaloniki. However, while monitoring we observed that wind was one factor that complicated source apportionment.

As mentioned in our results, we observed vastly different results based on the changes in wind patterns. Without studying the anemology of Thessaloniki at the time of monitoring, we cannot conclude what sources contributed to the concentration levels we measured. For days of high concentrations, the wind came from the gulf, but we are unsure if the source was shipping emissions, sea salt, Saharan dust, or from particles previously blown over the gulf from the western industrial centers.

In addition to the observations already mentioned, a future research group could better understand the contributions to pollution by investigating the patterns and trends of the industrial centers, the port, and residential heating. Educated predictions of their impacts would prepare researchers for what they should observe in their measurements.

In our data collection process, the only identifiable sources for spikes in PM or gasses were passive smoking and automotive traffic, respectively. By proper source attribution, future researchers could provide personalized solutions to better help café and restaurant owners. Researchers could also provide the trends they found from research and data collection to better protect these businesses from pollutant exposure.

Improve the use of micro-sensors for studying personal exposure.

We recommend further studies utilizing micro-sensors to monitor personal exposure. These sensors are an effective way to understand localized exposure because of their portability and accuracy, allowing them to travel where broad regional stations can not. After several weeks of data collection, we learned several aspects that contribute to the best use of micro-sensors.

We recommend using sensors certified to EU air quality directives, such as Envea micro-sensors, as it simplifies the data collection process by eliminating re-verification. Our team faced issues with measurement accuracy using uncertified sensors such as the Atmotube Pro. When approaching the data collection process, we recommend either carrying the sensors or leaving the sensors in an environment where concentrations can be analyzed. With either method, it is important to attribute spikes in concentrations to a source. Taking detailed qualitative notes coinciding with quantitative data collection can explain irregular occurrences.

We found a live feed of concentrations to be particularly helpful. With the Atmotube sensors, we would receive a notification to our mobile devices when concentrations reached unacceptable levels. This made source observations much easier to identify in real time. The utilization of micro-sensors can uncover places of exposure previously inaccessible or misrepresented by existing monitoring. In multiple restaurants we studied, local sources such as smoking or cooking contributed to concentration levels above WHO guidelines and at times, EU standards. Studies expanding the use of these sensors can reveal hazardous environments where people would be especially vulnerable to health risks. Knowing how to effectively use these sensors can lead to a more complete picture of Thessaloniki's air quality.

Increase local awareness and understanding of air pollution.

Based on our interviews about the perceptions and opinions on air pollution, workers in restaurants and cafés have limited awareness and understanding of air pollution. They often were unaware of the health impacts, where to get more information, and mitigation strategies. We recommend increased outreach through the mass distribution of the educational aspects in our pamphlet. Although our pamphlets were only distributed to a small group of stakeholders, they could be dispersed to more restaurant and café workers or additional residents of Thessaloniki. Partnering with city public health officials could help the information reach greater audiences.

We also recommend increasing public awareness by local government officials implementing an alert system to inform residents when pollution levels exceed WHO guidelines and EU limits. The application could filter live monitoring station data and trigger an alert when unsafe thresholds are reached. The alert could be similar to a smartphone notification or equivalent to the United States Wireless Emergency Alerts, and it would suggest residents stay indoors when concentrations are harmful to their health.

The information from our pamphlet could be incorporated into this application to educate residents when they receive an alert. These strategies could promote more awareness of air pollution's impact and help residents consider utilizing ways to reduce their exposure. Decreasing long-term exposure can positively impact their health as mentioned in the background.

Final Thoughts

Air quality in Thessaloniki is a prevalent problem and recent PM exceedances have drawn attention from the broader EU. Our research has shown that residents lack awareness and understanding of this issue. Specifically, residents are unaware of air pollution's severity, their personal exposure to it, or sources of reliable information. The issue of air pollution was exacerbated by Greece's economic recession. With the removal of restrictions on biomass burning, sources of air pollution have only worsened, leading to the condemnation by the EU, specifically for pollutant concentrations in Thessaloniki.

Our findings reveal that café and restaurant workers in the city are at risk for higher pollutant exposure levels above targets set by the EU and WHO. Future studies could help determine if these workers should be eligible for hazard pay from the Greek government, a topic that is marginally researched. Micro-sensors can measure localized pollutant concentrations to help devise tailored and feasible solutions. These sensors provide an opportunity to relate air pollution to people's everyday lives, such as at the cafés and restaurants they visit. Communicating with residents is critical to improving their understanding of air pollution and promoting mitigation techniques.

Bibliography

AIRTHINGS Project—An innovative tool to monitor air quality in the Balkan-Mediterranean region. (2020). https://www.interreg-balkanmed.eu/article/157_AIRTHINGS-Project---An-innovative-tool-to-monitor-air-quality-in-the-Balkan-Mediterranean-region

Air pollution: How it affects our health — European Environment Agency. (n.d.). [Page]. Retrieved February 19, 2023, from https://www.eea.europa.eu/themes/air/health-impacts-of-air-pollution

Air quality in Europe 2019—European Environment Agency. (n.d.). [Publication]. https://www.eea.europa.eu/publications/air-quality-in-europe-2019

Air quality standards—European Environment Agency. (n.d.). [Page]. Retrieved May 1, 2023, from https://www.eea.europa.eu/themes/air/air-quality-concentrations/air-quality-standards

Atmotube PRO - Wearable and portable air quality monitor. (n.d.). https://atmotube.com/atmotube-pro

Bourliva, A., Kantiranis, N., Papadopoulou, L., Aidona, E., Christophoridis, C., Kollias, P., Evgenakis, M., & Fytianos, K. (2018). Seasonal and spatial variations of magnetic susceptibility and potentially toxic elements (PTEs) in road dusts of Thessaloniki city, Greece: A one-year monitoring period. Science of The Total Environment, 639, 417–427. https://doi.org/10.1016/j.scitotenv.2018.05.170

Briggs, D. J., Collins, S., Elliott, P., Fischer, P., Kingham, S., Lebret, E., Pryl, K., Van Reeuwijk, H., Smallbone, K., & Van Der Veen, A. (1997). Mapping urban air pollution using GIS: A regression-based approach. International Journal of Geographical Information Science, 11(7), 699–718. https://doi.org/10.1080/136588197242158

Cao, C., Gao, J., Wu, L., Ding, X., & Zhang, X. (2017). Ventilation improvement for reducing individual exposure to cooking-generated particles in Chinese residential kitchen. *Indoor and Built Environment*, *26*(2), 226–237. https://doi.org/10.1177/1420326X16673215

Carratù, M., Chiarini, B., D'Agostino, A., Marzano, E., & Regoli, A. (2019). Air pollution and public finance: Evidence for European countries. Journal of Economic Studies, 46(7), 1398–1417. https://doi.org/10.1108/JES-03-2019-0116

Chang, H. (Sean), Capuozzo, B., Okumus, B., & Cho, M. (2021). Why cleaning the invisible in restaurants is important during COVID-19: A case study of indoor air quality of an open-kitchen restaurant. International Journal of Hospitality Management, 94, 102854. https://doi.org/10.1016/j.ijhm.2020.102854

Christaras, A. (2009). English: Mount Chortiatis in Thessaloniki prefecture, Greece. As seen from Thessaloniki Makedonia Airport Passenger Terminal (Southwestern aspect). [Photograph].https://commons.wikimedia.org/wiki/File:Chortiatis_mountain_%28with_observatory_at_peak%29,_Thessaloniki_prefecture,_Greece_01.jpg (CC BY-SA 3.0)

CO_2 emission performance standards for cars and vans. (n.d.). https://climate.ec.europa.eu/eu-action/transport-emissions/road-transport-reducing-co2-emissions-vehicles/co2-emission-performance-standards-cars-and-vans_en

Commission decides to refer GREECE to the Court of Justice. (n.d.). [Text]. European Commission - European Commission. Retrieved February 14, 2023, from https://ec.europa.eu/commission/presscorner/detail/en/IP_20_2151

Dani, R., Juyal, D., & Rawal, Y. (2021). A Critical Analysis of the Restaurant Industry's Effect on Environment Sustainability. 1, 435–442. https://doi.org/10.52152/spr/2021.165

Diapouli, E., Manousakas, M., Vratolis, S., Vasilatou, V., Maggos, T., Saraga, D., Grigoratos, T., Argyropoulos, G., Voutsa, D., Samara, C., & Eleftheriadis, K. (2017). Evolution of air pollution source contributions over one decade, derived by PM10 and PM2.5 source apportionment in two metropolitan urban areas in Greece. Atmospheric Environment, 164, 416–430. https://doi.org/10.1016/j.atmosenv.2017.06.016

Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe, CONSIL, EP, 152 OJ L (2008). http://data.europa.eu/eli/dir/2008/50/oj/eng

ENVEA. "Cairsens® O_3 + NO_2 | Micro-Sensors | Ambient." (n.d.) https://www.envea.global/s/ambient/micro-sensors/cairsens-o3-no2/.

European Environmental Agency—Greece—Air pollution country fact sheet. (2021). https://www.eea.europa.eu/themes/air/country-fact-sheets/2021-country-fact-sheets/greece

Fameli, K.-M., Kladakis, A., & Assimakopoulos, V. D. (2022). Inventory of Commercial Cooking Activities and Emissions in a Typical Urban Area in Greece. *Atmosphere*, *13*(5), Article 5. https://doi.org/10.3390/atmos13050792

Flocas, H., Kelessis, A., Helmis, C., Petrakakis, M., Zoumakis, M., & Pappas, K. (2009). Synoptic and local scale atmospheric circulation associated with air pollution episodes in an urban Mediterranean area. *Theoretical and Applied Climatology*, *95*(3), 265–277. https://doi.org/10.1007/s00704-008-0005-9

Gratsea, M., Liakakou, E., Mihalopoulos, N., Adamopoulos, A., Tsilibari, E., & Gerasopoulos, E. (2017). The combined effect of reduced fossil fuel consumption and increasing biomass combustion on Athens' air quality, as inferred from long term CO measurements. *Science of The Total Environment*, *592*, 115–123. https://doi.org/10.1016/j.scitotenv.2017.03.045

Greek Ministry of Environment and Energy (2019). *Air Pollution Measurement Data.* https://ypen.gov.gr/perivallon/poiotita-tis-atmosfairas/dedomena-metriseon-atmosfairikis-rypansis/

Grivas, G., Athanasopoulou, E., Kakouri, A., Bailey, J., Liakakou, E., Stavroulas, I., Kalkavouras, P., Bougiatioti, A., Kaskaoutis, D. G., Ramonet, M., Mihalopoulos, N., & Gerasopoulos, E. (2020). Integrating in situ Measurements and City Scale Modelling to Assess the COVID–19 Lockdown Effects on Emissions and Air Quality in Athens, Greece. *Atmosphere*, *11*(11), 1174. https://doi.org/10.3390/atmos11111174

Hellenic Statistical Authority. (2022). *Census Results of Publication and Housing.* https://www.statistics.gr/en/2021-census-res-pop-results

Household air pollution. (2022). https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health

History & Mission. (n.d.). http://www.perrotiscollege.edu.gr/history-mission-and-vision/

[Image of Perrotis College Logo]. (2017). https://www.perrotiscollege.edu.gr/strategic-plan/.

[Image of WPI Logo]. (2013). https://www.wpi.edu/offices/marketing-communications/resources

Kakaletsis, N., Tziomalos, K., Savopoulos, C., Riga, M., Bouziana, S., Spanou, M., Kostaki, S., Angelopoulou, S., Karatzas, K., & Hatzitolios, I. A. (2016). Outdoor air pollution and ischemic stroke severity: An ecological study in Thessaloniki. Atherosclerosis, 252, e22. https://doi.org/10.1016/j.atherosclerosis.2016.07.304

Karageorgou, K., Manoli, E., Kouras, A., & Samara, C. (2021). Commuter exposure to particle-bound polycyclic aromatic hydrocarbons in Thessaloniki, Greece. Environmental Science and Pollution Research, 28(42), 59119–59130. https://doi.org/10.1007/s11356-020-09475-9

Kasdagli, M.-I., Katsouyanni, K., de Hoogh, K., Lagiou, P., & Samoli, E. (2022). Investigating the association between long-term exposure to air pollution and greenness with mortality from neurological, cardio-metabolic and chronic obstructive pulmonary diseases in Greece. Environmental Pollution, 292, 118372. https://doi.org/10.1016/j.envpol.2021.118372

Kassandros, T., Gavros, A., Bakousi, K., & Karatzas, K. (2021). Citizens in the Loop for Air Quality Monitoring in Thessaloniki, Greece. In A. Kamilaris, V. Wohlgemuth, K. Karatzas, & I. N. Athanasiadis (Eds.), Advances and New Trends in Environmental Informatics (pp. 121–130). Springer International Publishing. https://doi.org/10.1007/978-3-030-61969-5_9

Kassomenos, P. A., Kelessis, A., Paschalidou, A. K., & Petrakakis, M. (2011). Identification of sources and processes affecting particulate pollution in Thessaloniki, Greece. *Atmospheric Environment*, *45*(39), 7293–7300. https://doi.org/10.1016/j.atmosenv.2011.08.034

Laumbach, R., Meng, Q., & Kipen, H. (2015). What can individuals do to reduce personal health risks from air pollution? *Journal of Thoracic Disease*, *7*(1), 96–107. https://doi.org/10.3978/j.issn.2072-1439.2014.12.21

Lainm, M. (2018). *Indoor market cooked food restaurant tables and chairs.* https://commons.wikimedia.org/wiki/File:HK_%E8%A7%80%E5%A1%98_Kwun_Tong_%E9%A7%BF%E6%A5%AD%E8%A1%97_Tsun_Yip_Street_indoor_Market_cooked_food_restaurant_tables_and_chairs_October_2018_IX2_01.jpg. (CC BY-SA 4.0).

Lee et al. (2020). *Adverse health effects associated with household air pollution: A systematic review, meta-analysis, and burden estimation study | Elsevier Enhanced Reader*. https://doi.org/10.1016/S2214-109X(20)30343-0

Lialias, G. (2023, March 24). Air - poison in Thessaloniki. Kathimerini. [Mechanical translation]. https://www.kathimerini.gr/society/562337167/aeras-dilitirio-sti-thessaloniki/

Matthaios, V. N., Triantafyllou, A. G., & Koutrakis, P. (2017). PM10episodes in Greece: Local sources versus long-range transport—observations and model simulations. *Journal of the Air and Waste Management Association*, *67*(1), 105–126. Scopus. https://doi.org/10.1080/10962247.2016.1231146

Mischyshyn, J. (2012). Enclosed Area at Front. [Photograph]. https://www.geograph.ie/photo/3055929. (CC BY-SA 2.0).

Mistrau, L. (2022). Outdoor seating. [Photograph]. https://commons.m.wikimedia.org/wiki/File:Outdoor_seating,_Lou_Mistrau,_pl_Horloge,_Avignon_-_2022-06-03.jpg. (CC BY-SA 4.0).

Moussiopoulos, N., Vlachokostas, Ch., Tsilingiridis, G., Douros, I., Hourdakis, E., Naneris, C., & Sidiropoulos, C. (2009). Air quality status in Greater Thessaloniki Area and the emission reductions needed for attaining the EU air quality legislation. Science of The Total Environment, 407(4), 1268–1285. https://doi.org/10.1016/j.scitotenv.2008.10.034

Munir, S. (2017). Analysing Temporal Trends in the Ratios of PM2.5/PM10 in the UK. Aerosol and Air Quality Research, 17(1), 34–48. https://doi.org/10.4209/aaqr.2016.02.0081

New metro improves quality of life in Thessaloniki-Projects—Regional Policy—European Commission. (2017, January 31). https://web.archive.org/web/20170131080758/http://ec.europa.eu/regional_policy/en/projects/greece/new-metro-improves-quality-of-life-in-thessaloniki

Özden Üzmez, Ö. (2018). ATMOSPHERIC CONCENTRATIONS OF INORGANIC POLLUTANTS (NO2, SO2 AND OZONE) IN ESKİŞEHİR: SPATIAL AND VERTICAL VARIATIONS, WEEKDAY-WEEKEND DIFFERENCES. *Anadolu University Journal of Science and Technology-A Applied Sciences and Engineering*, 1–1. https://doi.org/10.18038/aubtda.376520

Pantelic, J., Son, Y. J., Staven, B., & Liu, Q. (2023). Cooking emission control with IoT sensors and connected air quality interventions for smart and healthy homes: Evaluation of effectiveness and energy consumption. *Energy and Buildings*, *286*, 112932. https://doi.org/10.1016/j.enbuild.2023.112932

Papastergios, G., Tzoumaka, P., & Kelessis, A. (2019). Indoor and Outdoor Air Pollution Monitoring Developments in the Municipality of Thessaloniki – Preliminary Actions from Three European Funded Projects. *Bulletin of the Geological Society of Greece*, *55*, 1–18. https://doi.org/10.12681/bgsg.20611

Parliari, D., Giannaros, C., Papadogiannaki, S., & Melas, D. (2023). Short-Term Effects of Air Pollution on Mortality in the Urban Area of Thessaloniki, Greece. *Sustainability*, *15*(6), Article 6. https://doi.org/10.3390/su15065305

Pascal, M., Corso, M., Chanel, O., Declercq, C., Badaloni, C., Cesaroni, G., Henschel, S., Meister, K., Haluza, D., Martin-Olmedo, P., & Medina, S. (2013). Assessing the public health impacts of urban air pollution in 25 European cities: Results of the Aphekom project. *Science of The Total Environment*, *449*, 390–400. https://doi.org/10.1016/j.scitotenv.2013.01.077

Penza, M., Suriano, D., Cassano, G., Pfister, V., Alvisi, M., Rossi, R., Dambruoso, P. R., Trizio, L., & De Gennaro, G. (2012). P2.9.23 Portable Chemical Sensor-System for Urban Air-Pollution Monitoring. *Proceedings IMCS 2012*, 1767–1770. https://doi.org/10.5162/IMCS2012/P2.9.23

Petraki, V., Papantoniou, P., Korentzelou, A., George, Y. (2022). Public Acceptability of Environmentally Linked Congestion and Parking Charging Policies in Greek Urban Centers. *Sustainability*, *14*(15), 9208. https://doi.org/10.3390/su14159208

Pfleger, E., Adrian, C., Lutz, R., & Drexler, H. (2023). Science communication on the public health risks of air pollution: A computational scoping review from 1958 to 2022. Archives of Public Health, 81(1), 14. https://doi.org/10.1186/s13690-023-01031-4

Press, A. (2010, September 1). Greece bans smoking in enclosed public spaces. *The Guardian*. https://www.theguardian.com/world/2010/sep/01/greece-anti-smoking-measures

Progiou, A., Liora, N., Sebos, I., Chatzimichail, C., & Melas, D. (2023). Measures and Policies for Reducing PM Exceedances through the Use of Air Quality Modeling: The Case of Thessaloniki, Greece. *Sustainability*, *15*(2), 930. https://doi.org/10.3390/su15020930

Psefteli, M., Kavvadas, D., Karacosta, P., Cheristanidis, S., Dimitriadou, I., & Papamitsou, T. (2021). Air Quality Index study in the area of Thessaloniki. Archives of Hellenic Medicine. https://www.mednet.gr/archives/2022-6/pdf/838.pdf

Psistaki, K., Achilleos, S., Middleton, N., & Paschalidou, A. K. (2023). Exploring the impact of particulate matter on mortality in coastal Mediterranean environments. *Science of The Total Environment*, *865*, 161147. https://doi.org/10.1016/j.scitotenv.2022.161147

Pxfuel. (n.d.). Fold umbrella, set, house, Beer Garden, Chairs, Dining, Tables, dining tables, summer. https://www.pxfuel.com/en/free-photo-ogwff. (Public Domain Certification)

Revision of the Ambient Air Quality Directives. (n.d.). Retrieved February 13, 2023, from https://environment.ec.europa.eu/topics/air/air-quality/revision-ambient-air-quality-directives_en

Riley, R., de Preux, L., Capella, P., Mejia, C., Kajikawa, Y., & de Nazelle, A. (2021). How do we effectively communicate air pollution to change public attitudes and behaviours? A review. Sustainability Science, 16(6), 2027–2047. https://doi.org/10.1007/s11625-021-01038-2

Role of Member States and Commission. (2022, October 13). https://commission.europa.eu/law/application-eu-law/role-member-states-and-commission_en

Saffari, A., Daher, N., Samara, C., Voutsa, D., Kouras, A., Manoli, E., Karagkiozidou, O., Vlachokostas, C., Moussiopoulos, N., Shafer, M. M., Schauer, J. J., & Sioutas, C. (2013). Increased Biomass Burning Due to the Economic Crisis in Greece and Its Adverse Impact on Wintertime Air Quality in Thessaloniki. *Environmental Science & Technology*, *47*(23), 13313–13320. https://doi.org/10.1021/es403847h

Saliara, K. (2014). Public Transport Integration: The Case Study of Thessaloniki, Greece. *Transportation Research Procedia*, *4*, 535–552. https://doi.org/10.1016/j.trpro.2014.11.041

Saraga, D. E., Tolis, E. I., Maggos, T., Vasilakos, C., & Bartzis, J. G. (2019). PM2.5 source apportionment for the port city of Thessaloniki, Greece. *Science of The Total Environment*, *650*, 2337–2354. https://doi.org/10.1016/j.scitotenv.2018.09.250

Sarigiannis, D. A., Kontoroupis, P., Nikolaki, S., Gotti, A., Chapizanis, D., & Karakitsios, S. (2017). Benefits on public health from transport-related greenhouse gas mitigation policies in Southeastern European cities. *Science of The Total Environment*, *579*, 1427–1438. https://doi.org/10.1016/j.scitotenv.2016.11.142

Sarigiannis, D. A. (n.d.). *Combined or multiple exposures to health stressors in indoor built environments.*
Stefanakis, K. (2019). Air quality - PM. *Greek Ministry of Environment and Energy*. http://mapsportal.ypen.gr/maps/207

Technical Assistance Document for the Reporting of Daily Air Quality. (2018). AirNow; U.S. Environmental Protection Agency. https://www.airnow.gov/publications/air-quality-index/technical-assistance-document-for-reporting-the-daily-aqi/

Tran, V. V., Park, D., & Lee, Y.-C. (2020). Indoor Air Pollution, Related Human Diseases, and Recent Trends in the Control and Improvement of Indoor Air Quality. *International Journal of Environmental Research and Public Health*, *17*(8), 2927. https://doi.org/10.3390/ijerph17082927

US EPA. (2022, April 26). Health and Environmental Effects of Particulate Matter (PM) [Overviews and Factsheets]. https://www.epa.gov/pm-pollution/health-and-environmental-effects-particulate-matter-pm

Valavanidis, A., Vlachogianni, T., Loridas, S., & Fiotakis, C. (2015). Atmospheric Pollution in Urban Areas of Greece and Economic Crisis. Trends in Air Quality and Atmospheric Pollution Data, Research and Adverse Health Effects. *Dpt of Chemistry, University of Athens*, *1*, 1–27.

Vardoulakis, S., Giagloglou, E., Steinle, S., Davis, A., Sleeuwenhoek, A., Galea, K. S., Dixon, K., & Crawford, J. O. (2020). Indoor Exposure to Selected Air Pollutants in the Home Environment: A Systematic Review. *International Journal of Environmental Research and Public Health*, *17*(23), Article 23. https://doi.org/10.3390/ijerph17238972

Vlachokostas, C., Achillas, C., Moussiopoulos, N., Kalogeropoulos, K., Sigalas, G., Kalognomou, E.-A., & Banias, G. (2012). Health effects and social costs of particulate and photochemical urban air pollution: A case study for Thessaloniki, Greece. *Air Quality, Atmosphere & Health*, *5*(3), 325–334. https://doi.org/10.1007/s11869-010-0096-1

What are the WHO Air quality guidelines? (2021). https://www.who.int/news-room/feature-stories/detail/what-are-the-who-air-quality-guidelines

Yiannakou, A., Thoidou, E., & Pozoukidou, G. (2016). *Thessaloniki in the eyes of future planners: A collection of dissertation thesis* [Thesis, Aristotle University]. http://www.plandevel.auth.gr/aesop_hos_2016/sites/default/files/TMXA_Dissertation_Thesis.pdf

Appendix

Appendix A: Interview Questions and Consent Forms

Semi-Structured Interview Questions for Café and Restaurant Workers

1. How much time do you spend here per day? How often would you guess customers spend here?
2. If you have outdoor heaters, how often are they used, and for how long?
3. What differences in the air quality have you noticed in the (café/restaurant) since the smoking ban was effectively enforced?
4. What are your opinions on the air quality in your (café/restaurant)? Have you ever changed your behaviors or considered making changes because of the air quality?
5. Who do you trust to give reliable information on air quality?
6. Would you be interested to learn more about the air quality in your business?

— For selected businesses, we are doing kitchen measurements with —

1. Is it possible to see the kitchen?
2. What, if any, ventilation systems do you use in your kitchen while cooking?
3. How often are these ventilation systems on?
4. What kind of fuel do you use for cooking (propane, natural gas, etc.), and what kinds of cooking are done (deep frying, sautéing, etc.)?
5. What have you done to address air quality from cooking (smoke, fumes, etc.) in the restaurant? (i.e. adequate canopy hoods for workstations, properly sized ventilation system, clean grease filters, and regular maintenance)?

Interview Questions for Researchers

1. Through what statistics or quantities have you connected the health impacts with the levels of PM and NO_2? Specifically respiratory, cardiovascular, or neurological conditions.
2. What air pollution-related health conditions do you see the most often in Thessaloniki/Greece?
3. How can residents reduce their pollution exposure in indoor settings? Particularly in restaurants, cafés, and bars? What about in outdoor public areas?
4. What additional measures would you consider putting in place to improve air quality? What are the challenges to doing so?
5. Based on studies and the explanation from the recent condemnation of the EU Court of Justice, how significant is the sand from the Sahara desert to PM levels in Thessaloniki/Greece?
6. Do you recommend using EU air quality standards or WHO air quality recommendations when referencing unsafe pollutant concentrations?
7. What are effective ways of communicating dangerous air pollution levels to the public?
8. We are trying to make a pamphlet to help local restaurant and café owners. How can we generalize our findings and recommendations for such a brief time of collection? How can we make a meaningful impact on these café and restaurant owners?
9. Who can we point these owners to in order to learn more about air pollution?
10. If you know any, what studies are currently in progress about the reduction of pollution in the area of Thessaloniki? What publications of yours would you recommend we investigate more to aid our research?
11. Is there a question you think we should have asked? Do you think there is anything important not addressed by our questions?

Interview Questions for Health Officials

1. What are your thoughts on the state of air pollution in Thessaloniki?
2. To what extent are residents aware of the health effects caused by pollutants like PM and NO_2?
3. What was the consequence of the smoking ban on air quality? Is policy change an effective way of reducing health impacts? Do you know of any studies that discuss this?
4. What actions are being taken or regulations are in place to help reduce pollution in Thessaloniki/Greece?
    a. Are there jobs that are compensated for high exposure to air pollution? What does that compensation look like through pensions?
5. What resources are available for residents who want to learn more about air pollution and its health impacts, or those who want to take action to reduce their exposure to polluted air?
6. What additional measures would you consider putting in place to improve air quality? What are the challenges to doing so?
7. Is there a question you think we should have asked? Do you think there is anything important not addressed by our questions?

Simple Verbal Consent

Hello, my name is _____. I am a student at Worcester Polytechnic Institute in The United States. I am collecting information to help the faculty of Perrotis College to measure air quality in Thessaloniki. Would you be willing to take 5-10 minutes to answer a few questions?

A More Complete Verbal Preamble

We are a group of students from Worcester Polytechnic Institute (WPI) in the United States. We are interviewing Thessaloniki residents to learn more about local views and concerns about potential exposure to air pollutants. We hope this research will ultimately increase the extent of air monitoring and improve the public's awareness of the current air quality status in Thessaloniki.

Your participation in this interview is completely voluntary and you may withdraw at any time. Please remember that your answers will remain anonymous. No names or identifying information will appear in any of our project reports or publications.

This is a collaborative project between the faculty of the Environmental Science Department at Perrotis College and WPI, and your participation is greatly appreciated. If interested, we can provide further information and recommendations about air pollution.

Appendix B: Site Assessments Google Form

Qualitative Collection for Monitoring

1. Start Date
2. Start Time of Collection
3. End Date
4. End Time of Collection
5. Name of Location
6. Approximate Location/Area of Study
7. Weather Description (Ex: Sunny, rainy, cloudy, windy, post-rain)
8. Other Notable Conditions and Indoor Surroundings
9. Which sensors are being used? (Checkboxes for the sensors)
10. Where is the sensor located during collection? (image file upload required)
11. Other Notes for Analysis

Note. Questions were transcribed from the Google Form for readability and style.

Appendix C: Trifold Pamphlet

Figure 23. The English version of the trifold pamphlet

Figure 24. The Greek version of the trifold pamphlet

Appendix D: Additional Walking Data Map

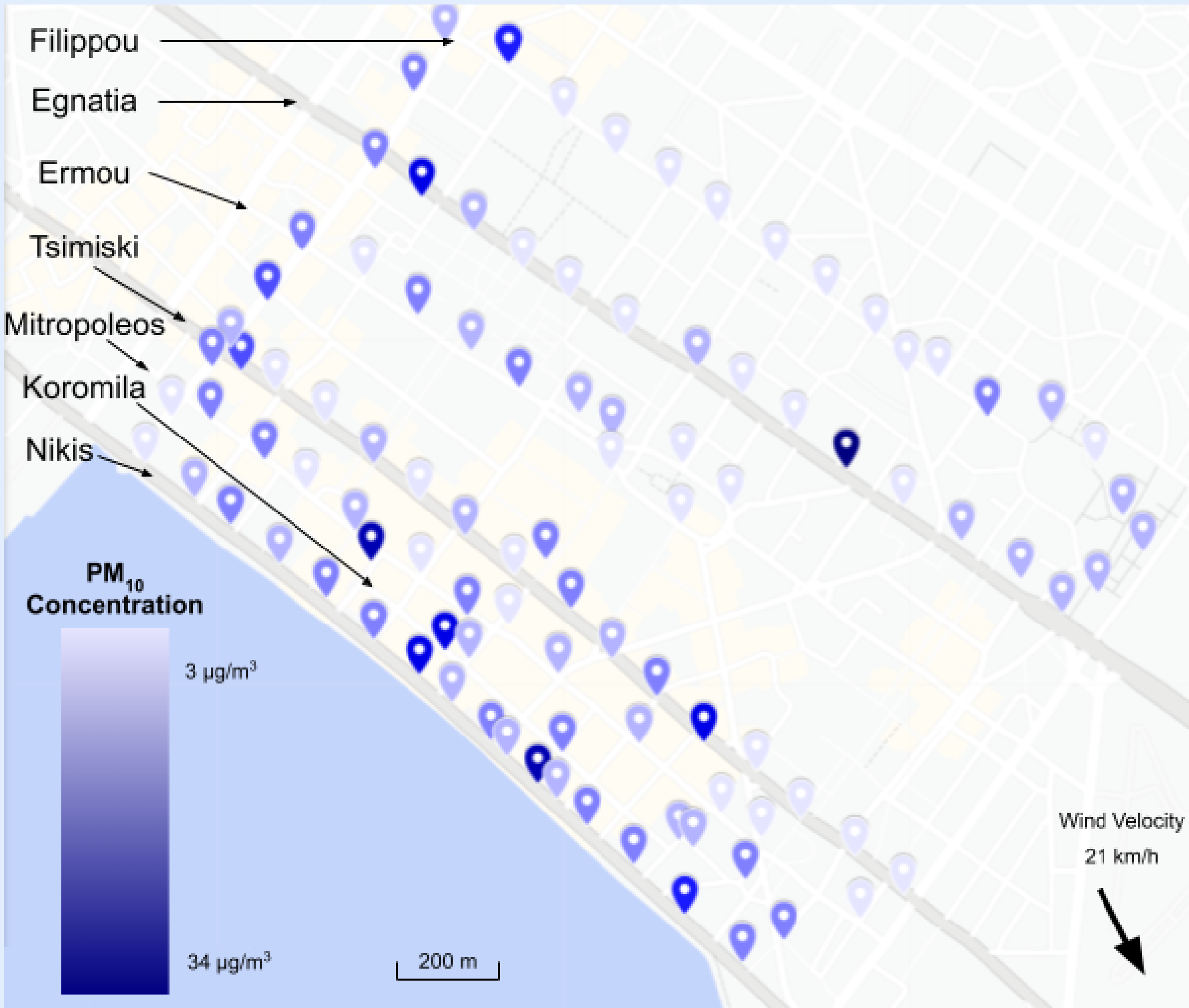

Figure 25. PM walking data of the Egnatia and Nikis neighborhoods on April 4

Note. The walk took place in the early evening when it was mostly sunny with little breeze. We observed several smokers in the Nikis area.

Appendix E: café/Restaurant 1-hour Average Data Table

Table 7: Café and restaurant 1-hour average pollutant concentrations

Date	Pseudonym	Time	Area of Study	1-hr $PM_{2.5}$ AVG	1-hr PM_{10} AVG	1-hr NO_2 AVG	1-hr SO_2 AVG	1-hr CO AVG
3/20	Café α	Mid-day	Ano Poli	12.17	13.18	41.95	129.81	—
3/20	Café β	Mid-day	Ano Poli	14.26	15.28	12.02	—	546
3/20	Restaurant α	Mid-day	Ano Poli	11.55	12.56	13.97	131.09	—
3/20	Restaurant β	Mid-day	Ano Poli	11.96	12.99	11.61	—	6856
3/23	Café α	Mid-day	Egnatia	22.05	23.03	29.44	—	1179
3/23	Café β	Mid-day	Egnatia	28.76	29.76	32.16	88.42	—
3/23	Restaurant α	Mid-day	Egnatia	20.54	21.56	27.37	—	781
3/23	Restaurant β	Mid-day	Egnatia	21.18	22.90	27.98	99.671	—
3/24	Café α	Mid-day	Nikis	20.42	21.45	19.81	—	892
3/24	Café β	Mid-day	Nikis	18.97	20.03	26.80	103.25	—
3/24	Restaurant α	Mid-day	Nikis	12.89	13.89	42.68	—	1075
3/24	Restaurant β	Mid-day	Nikis	16.19	17.19	33.18	120.84	—
3/27	Café α	Mid-day	Egnatia	9.33	10.33	53.59	165.36	—
3/27	Café β	Mid-day	Egnatia	11.42	12.47	31.29	—	815
3/27	Restaurant α	Mid-day	Egnatia	7.9	8.95	22.97	153.54	—
3/27	Restaurant β	Mid-day	Egnatia	9.77	10.75	19.49	—	875
3/28	Café α	Mid-day	Ano Poli	4.56	5.56	5.61	—	298
3/28	Café β	Mid-day	Ano Poli	3.88	4.87	11.20	60.54	—
3/28	Restaurant α	Mid-day	Ano Poli	3.78	4.78	7.69	—	1733
3/28	Restaurant β	Mid-day	Ano Poli	3.13	4.16	9.76	31.56	—
3/30	Café α	Mid-day	Nikis	8.48	9.48	60.10	—	2559
3/30	Café β	Mid-day	Nikis	19.28	20.51	—	—	—
3/30	Restaurant α	Mid-day	Nikis	7.83	8.83	32.22	—	1468
3/30	Restaurant β	Mid-day	Nikis	8.58	9.57	—	—	—
4/4	Café α	Evening	Nikis	15.55	16.57	31.96	—	1737
4/4	Café β	Evening	Nikis	10.87	11.83	32.73	200.72	—
4/4	Restaurant α	Evening	Nikis	16.93	18.03	44.44	—	1576
4/4	Restaurant β	Evening	Nikis	11.33	12.35	59.75	119.93	—
4/5	Café α	Mid-day	Egnatia	5.57	6.6	—	—	599
4/5	Café β	Mid-day	Egnatia	4.20	5.25	23.16	86.8	—
4/5	Restaurant α	Mid-day	Egnatia	6.38	7.33	—	—	4304
4/5	Restaurant β	Mid-day	Egnatia	5.77	6.74	31.61	110.87	—
4/11	Café α	Mid-day	Ano Poli	17.12	18.08	—	—	638
4/11	Café β	Mid-day	Ano Poli	17.83	18.84	22.04	140.14	—
4/11	Restaurant α	Mid-day	Ano Poli	14.65	15.73	—	—	1496
4/11	Restaurant β	Mid-day	Ano Poli	11.51	12.52	8.61	98.38	—

Table 8. Café and restaurant qualitative observations

Date	Pseudonym	Environment	Weather	Wind Speed (km/h)	Wind Direction (deg South)
3/20	Café α	Fully-Enclosed Outdoor	Sunny, mostly clear skies	6	120
3/20	Café β	Semi-Enclosed Outdoor	Warm, sunny, light wind	6	120
3/20	Restaurant α	Semi-Enclosed Outdoor	Sunny, clear skies	6	120
3/20	Restaurant β	Indoor	warm, sunny	6	120
3/23	Café α	Fully-Enclosed Outdoor	Sunny, partially cloudy, humid, no wind	7	100
3/23	Café β	Outdoor	Sunny, light breeze	7	100
3/23	Restaurant α	Outdoor	Sunny with a few clouds, light breeze	7	100
3/23	Restaurant β	Indoor	Mostly Sunny, no wind	7	100
3/24	Café α	Outdoor	Sunny, warm, few clouds, constant light sea breeze	7	240
3/24	Café β	Outdoor	sunny, slight breeze, warm	7	240
3/24	Restaurant α	Indoor	Sunny, light breeze	7	240
3/24	Restaurant β	Outdoor	Sunny, warm, very light breeze	7	240
3/27	Café α	Outdoor	Sunny, clear skies, light wind (from traffic)	16	130
3/27	Café β	Semi-Enclosed Outdoor	Sunny, no wind	16	130
3/27	Restaurant α	Outdoor	Sunny, clear, very light wind	16	130
3/27	Restaurant β	Semi-Enclosed Outdoor	sunny, no wind	16	130
3/28	Café α	Semi-Enclosed Outdoor	Extremely Windy, cold, clear skies, it rained yesterday.	28	190
3/28	Café β	Semi-Enclosed Outdoor	Partial cloudy, very windy to SE	28	190
3/28	Restaurant α	Indoor	Very windy, cold, rained yesterday, clear skies	28	190
3/28	Restaurant β	Fully-Enclosed Outdoor	Partially Sunny, very windy	28	190
3/30	Café α	Outdoor	Mostly Sunny, warm, little to no breeze	11	150
3/30	Café β	Fully-Enclosed Outdoor	Sunny, light northern breeze	11	150
3/30	Restaurant α	Outdoor	Mostly Sunny, little to no breeze	11	150
3/30	Restaurant β	Indoor	Sunny, light breeze	11	150
4/4	Café α	Outdoor	Sunny, partly cloudy l, little to no wind.	21	330
4/4	Café β	Outdoor	Sunny, warm, little to no wind	21	330
4/4	Restaurant α	Outdoor	Clear skies, little to no breeze. Colder as the sun sets	21	330
4/4	Restaurant β	Semi-Enclosed Outdoor	Sunny, warm, little to no wind	21	330
4/5	Café α	Outdoor	Sunny, windy, chilly	20	300
4/5	Café β	Indoor	Cloudy, light wind	20	300
4/5	Restaurant α	Indoor	Sunny, windy	20	300
4/5	Restaurant β	Outdoor	Sunny, light breeze	20	300
4/11	Café α	Semi-Enclosed Outdoor	Partially cloudy, breezy	20	315
4/11	Café β	Fully-Enclosed Outdoor	Partially cloudy, breezy	20	315
4/11	Restaurant α	Fully-Enclosed Outdoor	Partially cloudy, breezy	20	315
4/11	Restaurant β	Outdoor	Partially cloudy, breezy	20	5