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THAVIVANH NAMVONG
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Hungarian University of Agriculture and Life Sciences

Szent István Campus

Institute of Environmental Sciences

BSc Environmental Engineering

Examining PM10 and PM2.5 concentration in Gödöllő

Supervisor : Dr. Gábor Géczi

Associate professor

Institute: Institute of Environmental Sciences

Author: Thavivanh Namvong
Neptun: JHWS05

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Abstract

Air pollution, specifically caused by particulate matter (Cichowicz & Dobrzański), like PM_{10} and $PM_{2.5,}$ is a concern that greatly impacts the health of the public and the environment. The World Health Organization (Organization) attributes millions of deaths each year to air pollution, both indoors and outdoors. The research aims to investigate the origins of particulate matter in the city of Gödöllő, Hungary and comparatively examine the varying levels of PM_{10} and $PM_{2.5}$ in sub-urban and urban settings along with factors that affect these levels. To understand the dynamics of particulate matter in Gödöllő, data was collected from two locations where sensors were installed: Sensor A, which was located outside of the city center near the highway, and Sensor B situated in the city center. The Honeywell HPMA115S sensor was utilized to monitor levels of PM_{10} and $PM_{2.5}$ from February 17th to May 1st 2023 spanning over the transition end winter to spring season. Other environmental variables, like temperature, humidity, and pressure were also recorded to investigate how they relate to PM levels. The results suggest that PM_{10} and $PM_{2.5}$ levels tend to be elevated in the areas closer to the highways and where wood-based heating systems are installed have PM_{10} and PM2.5 concentration averages of 24.6 µg/m³ and 19.2 µg/m³ respectively. The sensor is not near the highway and where center heating system like sensor B has a PM_{10} and $PM_{2.5}$ concentration average of 13.1 µg/m³ and 10.4 µg/m³ respectively. In addition, $PM_{2.5}$ concentrations of sensor A exceeded WHO standards 75% of the data collected in Gödöllő. Statistical analysis such as Pearson correlation analysis, revealed a correlation between temperature and particulate matter levels suggesting that higher temperatures are linked to lower concentrations of particulate matter possibly due to enhanced dispersion in the atmosphere and low usage of heating systems. On the other hand, pressure and humidity displayed positive associations with PM levels. The study's findings have important implications for public health policies and environmental regulations in Hungary. The study highlights the importance of implementing policies to enhance air quality with a focus on controlling emissions from vehicles and switching to modern heating systems. These findings enhance our knowledge of where particulate matter originates in Gödöllő and lay the groundwork, for creating measures to combat air pollution and its related health hazards.

List of Symbols

P	Atmospheric pressure	[hPa] or[bar]
PM_1	Concentration of particles with an aerodynamic diameter of less than 1 micron	[μg/m³]
PM_{10}	The concentration of particles with an aerodynamic diameter of up to 10 microns	[μg/m³]
$PM_{2.5}$	Concentration of particles with an aerodynamic diameter of less than 2.5 microns	[μg/m³]
RH	Relative humidity	[-]
T	Temperature	[°C]
V	Wind speed	[m/s]

Abbreviation

AAQDs	The EU Ambient Air Quality Directives
AQGs	WHO Global Air Quality Guidelines
COPD	Chronic obstructive pulmonary disease
DNA	Deoxyribonucleic
EPA	Environmental Protection Agency
EU	The European Union
IARC	International Agency For Research On Cancer
NAAQS	National Ambient Air Quality Standards
NOx	Nitrogen oxides
PAHs	Polycyclic aromatic hydrocarbons
PM	Particulate Matter
SO_2	Sulfur dioxide
WHO	World Health Organization

1. Introduction

Air pollution refers to the presence of substances in outdoor environments that alter the natural composition of the air. These pollutants can originate from industrial emissions, household appliances and transportation as well as natural events such as wildfires and volcanic eruptions. The emissions from these sources introduce elements into the atmosphere, such as particulate matter (Cichowicz & Dobrzański), carbon monoxide, ozone, nitrogen dioxide and sulfur dioxide causing impacts on human health and the environment. Air pollution presents a concern for the environment and public health as stated by the World Health Organization (Organization) which links around 7 million deaths each year due to air pollution (Organization, 2014).

PM_{10} and $PM_{2.5}$ refer to particulate matter with different sizes that are critical indicators of air quality. PM_{10} comprises of particles with diameters of 10 micrometers or smaller, while $PM_{2.5}$ consists of finer particles with diameters of 2.5 micrometers or smaller. Due to their smaller size, $PM_{2.5}$ particles are considered more hazardous to health, as they can penetrate deeper into the lungs and even enter the bloodstream, potentially causing respiratory and cardiovascular diseases (Pascal et al., 2014). Particulate matter PM_{10} and $PM_{2.5}$ significantly impact health concerns by causing respiratory and cardiovascular diseases, and reduced life expectancy (Thangavel, Park, & Lee, 2022).

Particulate matter (Cichowicz & Dobrzański) can originate directly from sources like particles or form in the atmosphere through chemical reactions involving gases such as sulfur dioxide (Cichowicz & Dobrzański) nitrogen oxides (Peel et al.). Specific organic compounds. These organic compounds can be released by both sources like trees and plants and human made sources such as operations and vehicle exhaust emissions. $PM_{2.5}$ being smaller in size, are suspended in the air and persists for long periods. They can travel greater distances which leads to health effects in areas which are distant from the source. Environmental concerns related to particulate pollution include deteriorating air quality, visibility, and harm to ecosystems caused by acidification and eutrophication (Wu & Zhang, 2018). Various studies examine the effects and variations of PM10 and PM2.5 in different environments. For example, Pascal et al. (Pascal et al.) investigated the short-term impacts of PM10 and PM2.5 on mortality in nine French cities, finding significant interactions between warm days and particulate matter. In another study, Wang et al. (Li, Chen, Zhao, Wang, & Tao) examined the spatial and temporal variations of PM10 and PM2.5 concentrations across China, demonstrating that factors like urbanization and industrial activity significantly impact air quality. Additionally, Xue et al. (Luo, Bing, Luo, Wang, & Jin) analyzed the similarities and differences in PM10 and PM2.5 concentrations, chemical compositions, and sources in Hefei City, China, highlighting that environmental conditions and human activities contribute to these variations.

In 2021, the European Union recorded a staggering figure of 253,000 deaths due to $PM_{2.5}$. Despite a 41% decrease in air pollution-related deaths since 2005, PM continues to pose public health risks (Agency, 2023). Around 9,500 deaths due to $PM_{2.5}$ in Hungary were recorded in 2020 highlighting the threat posed by particulate pollution (Medve, 2022).

Given these significant public health implications, this study aims to investigate the sources of particulate matter in Gödöllő, a city near Budapest, Hungary. Air quality concerns there persist due to vehicle exhaust emissions and the use of wood burning for heating. This research seeks to investigate the origins of PM_{10} and $PM_{2.5}$ pollutants in Gödöllő and compare the differences in their levels between the city center and suburban areas. Moreover, the effect of environmental factors such as temperature, humidity, wind speed, and atmospheric pressure was studied since these factors influence PM concentrations (Ferenczi et al., 2021). Understanding the particulate matter concentrations in Gödöllő is essential for developing targeted environmental policies and public health strategies. This research highlights the impacts of PM pollution with a focus on how traffic and household heating impact air quality. By tackling these issues the research contributes to a comprehension of air pollution in Hungary aiding in urban planning. The insights gained from this study can assist policymakers in devising measures to enhance air quality and mitigate the health hazards linked to PM.

1.1 Objectives of the study

The objective of this study is to analyze the environmental and social factors influencing $PM_{2.5}$ and PM_{10} concentrations in Gödöllő city center and surrounding areas. The specific objectives are:

1) Measuring and comparatively analyzing the levels of PM_{10} and $PM_{2.5}$ in two areas; the city center of Gödöllő and a rural vicinity near the city using Honeywell HPMA115S sensors.

2) Comparing PM concentrations between the 2 locations to determine the impact of different sources, such as vehicular emissions and residential heating.
3) Examining the correlation between PM levels and environmental factors such as temperature, humidity, wind speed, and pressure to understand their influence on PM concentrations.

1.2 Research questions

1) What are the primary sources of PM_{10} and $PM_{2.5}$ in Gödöllő, particularly in the city center and outside of the center near the highway?
2) How do temperature, wind speed, humidity, and atmospheric pressure affect PM concentrations in these locations?
3) How do seasons and heating systems usage affect PM concentrations at these locations?

Focusing on Gödöllő, the research aims to support planning efforts and contribute to broader initiatives aimed at curbing air pollution and its associated health hazards. Due to limitations of time and resources, this research concentrated on two areas of Gödöllő the city center and a rural zone near a highway with data collection spanning three months. Furthermore, data collection took place across two seasons during this timeframe potentially influencing the consistency of variables. Despite these constraints, the study provides valuable insights into air quality in Gödöllő while laying a foundation for exploration into PM level's effects on public health and the environment.

2. Literature Review

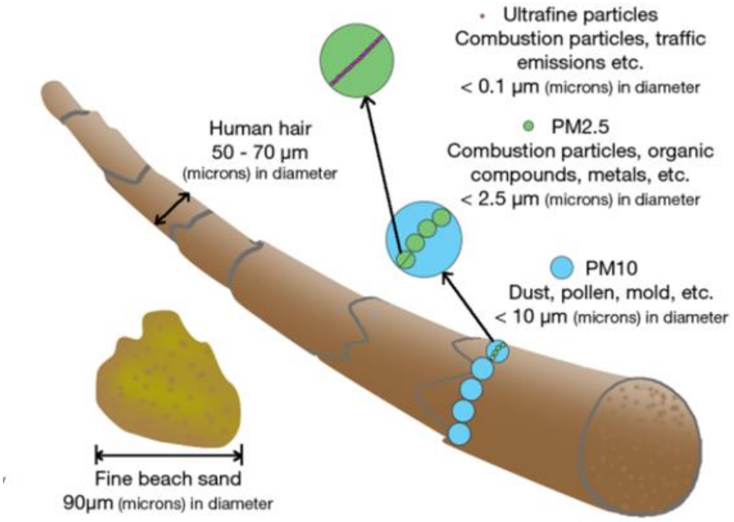
2.1 Particulate Matter

Particulate matter is a complex mixture of minute particles and droplets suspended in the air. The particles differ from one another in size, composition, origin, and other properties, but the classification of particles based primarily on their aerodynamic diameter is clinically relevant because this will determine where in the respiratory tract they will penetrate and deposit (Seinfeld & Pandis, 2016). They are a heterogeneous mixture of solids and liquids of various sizes, forms, and structures. Their minute size make them to susceptible to be inhaled, making them dangerous to human health. In the air, they give rise to what we recognize as mist, the diffraction of sunshine by these very tiny particles. Additionally, PM emissions are a byproduct of industrial activities and the social lifestyle in places where humans live or work. They are dangerous primarily to human respiratory systems since they cause the corresponding ailments. Because of the risk to human life and environment, PM is a public health and meteorological concern (Pope Iii & Dockery, 2006).

PM_{10} are coarse particles having a diameter of between 2.5 to 10 µm which are depicted as blue dots in Figure 1. These particles can be captured by the nose and throat and provoke secretion when inhaled and penetrate the bronchi into the lungs (Seinfeld & Pandis, 2016). On the other hand, $PM_{2.5}$ are tiny particles measuring less than 2.5 µm in diameter and are Represented as green dots in Figure 1. Due to their size, these particles can penetrate deeper into the lungs' alveoli as far as the bloodstream (Thangavel et al., 2022). $PM_{2.5}$ sources include combustion processes, such as motor vehicles, power stations, industrial operation plants, household wood burning, and volcanic emissions.

The health effects of PM are worrisome because these particles can transport substances, such as metals and organic compounds deep, into the lungs and bloodstream leading to serious health concerns (Talwar, Bharati, & research, 2018).

Figure 1: Particulate Matter size compare to human hair (Solutions, 2017)



2.2 Physical and chemical characteristics of Particulate Matter

Particulate Matter can be defined as that tiny particle in the air that creates harmful effects on human health. Its physical properties which include the size, shape, and surface area play a critical role in identifying its atmospheric behavior and how it interacts with human health. Its size ranges from a few nanometers to several micrometers and it can either be spherical in shape or irregular. In studies of health the term surface area is very vital as it defines the amount of toxic substances that the PM can adsorb and also the interaction with tissues of the biological system. The smaller particles have a large surface-to-volume ratio which helps the toxic substances adsorb and cause harmful effects through the respiratory systems (RISTOVSKI et al., 2012) .

Its chemical composition is very complex. It depends on the origin of the particle and the conditions under which they are formed. Organic compounds together with inorganic ions, metals, and elemental carbon compose these particles. The organic components of the PM are naturally exuded from sources of vegetation, forest fires and anthropogenic, such as those from vehicular exudates and several industrial processes. Among the inorganic ions are the sulfates and nitrates often sourced in combustion, among atmospheric reactions of sulfur dioxide and nitrogen oxides, respectively. Some of these metals are lead, arsenic, and cadmium which are commonly associated with industrial emissions and have a toxic effect on human health. Elemental carbon more commonly known as black carbon is a large constituent of soot formed from incomplete combustion. It largely contributes to the absorption of sunlight and has a big impact on the Earth's climate (Fuzzi et al., 2015).

2.3 Natural and anthropogenic Sources of Particulate Matter

Particulate matter (PM) a critical air pollutant originates from various natural and anthropogenic sources each contributing distinctively to the environmental and health impacts observed globally and locally. From volcanic emissions particulate matter can be transported around the Earth therefore acting on the climate and air quality. The volcanic particles may bring long-lasting changes to atmospheric conditions and have immediate health impacts on the exposed population following ashfall (Gudmundsson, 2010) .

Dust storms can cause the phenomena of lifting minerals from arid and semi-arid regions of the world into the atmosphere. Likewise, the wind forces the particulate matter on a continental scale derived from the soil, including quartz, calcite, and gypsum thousands of kilometers away from the source of origin. These particles contribute to the global burden of PM and can impact respiratory health in distant populations (Goudie, 2014).

Furthermore, forest and grassland fires are direct producers of large amounts of particulate matter. The emitted compounds have complex mixtures of organic and inorganic compounds which are transported from the source region to other areas degrading the local air quality. Thus, these emissions do affect the health of the people not only locally but also very far away in the downwind direction of the fires because the fine particles can be transported over long distances (Reid et al., 2016).

As for the anthropogenic sources road traffic is known to be a contributing source to high PM levels in cities. Vehicle emissions deteriorate urban air quality with its consequent impact on public health. Studies indicate that this kind of relationship between vehicular emissions led to increased pollution in an urban setting (Sailesh & Rajasekhar, 2016).

Industrial activities lead to the release of pollutants that are known to have an impact on air quality and human health. These pollutants come in sizes and chemical compositions influencing pollution levels at regional levels. Current studies in this area examine these effects to create strategies for controlling emissions (Giannakis et al., 2019).

In regions like Central Europe like burning wood, coal, and other solid fuels for heating and cooking is a prevalent source of PM. This combustion process releases particles that can penetrate indoor and outdoor environments significantly impacting air quality and human health in these areas (Archer-Nicholls et al., 2016).

Similarly, agricultural activities which include plowing, harvesting, and tending to livestock management that occur outdoors. Generally, the activities and operations involved with agriculture produce high percentages of airborne particles contributing to the global burden of PM and hence affecting the health of the populations staying far. This has brought to light the effects of the practice on air quality and climate. Specifically, past research has examined the effects of agricultural practices on air quality and climate, emphasizing the need for policy and regulatory responses (Aneja, Schlesinger, & Erisman, 2009) .

2.4 Health Effects of Particulate Matter

The health implications of particulate matter are extensive. An inhalation of PM can lead to acute respiratory symptoms such as coughing, irritation of the throat and shortness of breath. It worsens cases such as asthma and chronic obstructive pulmonary disease (COPD) by causing inflammation of the airways and decreased lung function. Long-term exposure involves a considerably higher risk of getting respiratory infections and chronic bronchitis (Zhou et al., 2020). There is substantial evidence linking long-term exposure to particulate matter with an increased risk of lung cancer (Pope III et al., 2002). The International Agency for Research on Cancer (IARC) has stated that outdoor air pollution and particulate matter (PM) are considered to be cancer-causing agents for humans. These particles can transport chemicals into the parts of our lungs leading to DNA harm and potentially triggering the growth of tumors.

Research has also shown the effects of particulate matter on the brain leading to decline and a higher risk of neurological conditions like Alzheimer’s and Parkinson's. While the specific ways in which this occurs are not fully clear but potential factors may include stress, inflammation, and disturbances, in the blood-brain barrier (González-Maciel, Reynoso-Robles, Torres-Jardón, Mukherjee, & Calderón-Garcidueñas, 2017).

Particulate matter (PM) can have more of an adverse effect on certain groups of people than others. These groups include children, the elderly, and those who already have health problems. For children being exposed to PM can hinder lung growth and function trigger infections and worsen asthma symptoms (Landrigan, Schechter, Lipton, Fahs, & Schwartz, 2002). Pregnant women who are exposed to levels of PM face a likelihood of experiencing complications like premature birth and having babies with low birth weight (Dominici et al., 2006).

Some Case Studies from Different Regions of Epidemiological studies on PM_{10} and $PM_{2.5}$ found:

i. A case study by (Zanobetti et al. 2009). in the United States found a significant association between exposure to PM2.5 and increased hospital admissions for cardiovascular and respiratory diseases
ii. A case study by (Medina, Plasencia, Ballester, Mücke, & Schwartz) in European cities has demonstrated that both short- and long-term exposure to PM_{10} and $PM_{2.5}$ can lead to a wide range of adverse health effects and even low concentrations of PM have been shown to affect health, suggesting there is no safe threshold
iii. A case study by (Liao, Ju, Zhou, Gao, & Pan) in China shows that exposure to $PM_{2.5}$ increases the risk of lung cancer. This risk is higher in areas closer to pollution sources. The findings stress the need for region-wide efforts to control air pollution and reduce health risks.
iv. A case study by (Peel et al.) in Atlanta, Georgia found that higher levels of pollution were associated with an increased likelihood of emergency visits for heart problems such as heartbeat and congestive heart failure among individuals with both hypertension. Those with diabetes and chronic obstructive pulmonary disease (COPD) also faced a risk of issues due to elevated pollution levels. The effect of air pollution on heart health was notably impacted by the presence of conditions, particularly fine particulate matter (particles smaller, than 10 micrometers in diameter).
v. A case study by (Szigeti et al.) conducted in Budapest assessed the chemical composition and oxidative potential of $PM_{2.5}$ highlighting the seasonal variability and health impacts of air pollutants in an urban setting. The study found that $PM_{2.5}$ composition was mainly made up of matter and secondary inorganic ions showing concentrations from 2010 to 2013. This research sheds light on the air quality challenges in areas of Hungary and their possible effects on public health.

2.5 Environmental Impacts of Particulate Matter

a) Effect on Climate Change

Particulate matter such as PM_{10} and $PM_{2.5}$ plays a role in chemistry and has significant implications for climate change. These tiny particles have the ability to affect how energy moves through the Earths atmosphere by either soaking up or scattering sunlight. Black carbon found in $PM_{2.5}$ is good at absorbing sunlight. Adding to warming. Conversely other components of particulate matter can bounce sunlight back into space causing cooling effects. Moreover these particles act as centers for cloud formation which can lead to both warming and cooling impacts on the climate. The overall effect on climate change depends on factors like the type of particles their concentration levels and where they are situated in the atmosphere (Boschung, 2013).

b) Impact on Ecosystems and Biodiversity

The presence of particulate matter in the environment can have detrimental effects on ecosystems and biodiversity:

Soil Pollution the deposition of particulate matter can result in soil contamination changing its composition and impacting the cycle of nutrients. This pollution may hinder the growth of plants. Diminish soil fertility influencing the well-being of land-based ecosystems. Moreover, the buildup of metals and harmful compounds from particulate matter in the soil can have effects on essential microorganisms crucial for ecosystem processes (Luo et al., 2019).

Water Pollution by transporting chemicals and toxins that impact the clarity and quality of the water. These floating particles can block sunlight from reaching underwater which disrupts the process of photosynthesis in plants and has consequences for lives . Additionally, when PM settles in bodies of water it can result in the buildup of toxins within the food chain presenting dangers to biodiversity and the overall health of water resources (Schwarzenbach et al., 2010).

The health of plants can be negatively impacted by PM as it blocks the stomata on leaves decreasing photosynthesis and hindering plant growth. When acidic or harmful particulate matter settles on plant surfaces it can harm plant tissues making them more vulnerable to diseases and pests. This overall effect on plant health can cause a drop in productivity and a reduction in plant variety, which could have consequences for the stability and resilience of ecosystems (Nowak, Hirabayashi, Bodine, & Hoehn, 2013).

2.6 Influences on Particulate Matter Levels

a) Meteorological

Meteorological influences on particulate matter (PM) levels encompass how weather conditions affect the concentration, distribution, and chemical composition of these particles in the atmosphere. Here's how specific meteorological factors impact PM levels:

Temperature influences the levels of particulate matter by affecting how quickly chemical reactions the stability of the atmosphere. Warmer temperatures can speed up the production of aerosols causing an uptick in particulate matter levels. This impact is most noticeable in the summer months when greater solar radiation boosts reactions resulting in amounts of secondary organic aerosols a significant element of $PM_{2.5}$ (D. Zhao et al., 2019).

Humidity affects PM concentrations by influencing particle hygroscopicity, where particles soak up water vapor they get bigger and heavier. This not boosts the $PM_{2.5}$ levels. Also changes how the particles look impacting what we can see and how clean the air is. The link, between humidity and PM is intricate since it can cause particles to either grow or be removed based on the surrounding environment (Guo et al., 2018).

Atmospheric pressure plays a crucial role in the dispersion of PM High pressure weather systems tend to cause still air conditions with wind speeds, which can cause pollutants like PM to gather close to the ground. On the hand low pressure systems are linked to winds and increased vertical mixing helping pollutants disperse more effectively and possibly decreasing ground level PM levels (Samad, Vogt, Panta, & Uprety, 2020).

wind plays a role in carrying and spreading PM. It has the power to transport particles over distances impacting the air quality. In regions where they originate well as those downwind. The wind's capacity to scatter or accumulate pollutants in a location is determined by its velocity, direction and the surrounding geographical characteristics (El-sharkawy & Zaki, 2016).

b) Seasonal and Geographic

PM levels change throughout the year because of factors like where pollution comes from the weather and how chemicals in the air interact. In places with four seasons, winter usually has

PM because of pollution from heating and air that doesn't move much. Summer can also have PM, from smog caused by sunlight and new particles forming in the air (X. Zhao et al., 2009).

In terms of location the levels of PM are impacted by factors like development landscape features and the dominant weather conditions. Cities usually have elevated levels of PM due to sources like traffic and industrial operations. Landscape characteristics, such as valleys or basins enclosed by mountains can trap pollutants. Result in increased PM levels in those regions (Zalakeviciute, López-Villada, & Rybarczyk, 2018).

c) Transportation

Urban air quality is greatly impacted by transportation because of the release of particulate matter (PM), from vehicles. The link between transportation and the deterioration of city air quality is connected to the pollutants emitted by vehicles fluctuations in traffic density and the proximity of roads to areas. Vehicles, those running on diesel fuel play a role in PM pollution by emitting both primary exhaust particles and secondary particles formed from nitrogen oxides (NOx) and sulfur dioxide (SO2). The levels of $PM_{2.5}$ and NOx emissions from diesel vehicles are particularly high contributing to pollution. These emissions can vary depending on factors, like vehicle type, age, maintenance practices and fuel quality (Harrison, Jones, & Lawrence, 2004) . $PM_{2.5}$ and NOx are particularly concerning due to their ability to penetrate deeply into the body and cause heart-related health problems (Gualtieri et al., 2020).

In cities the amount of particulate matter (PM) is greatly affected by the volume of traffic. More traffic results, in increased emissions causing levels of PM. Areas with traffic congestion, such as streets and intersections where vehicles move slowly or stop frequently become focal points for air pollution increasing PM concentrations. Additionally, pollution levels change throughout the day and, across seasons usually peaking during rush hours and colder times of the year (Keuken et al., 2014).

Various research studies have compared the air quality, near roads to that in areas located away from direct traffic sources. These studies consistently reveal that regions closer to heavy traffic exhibit levels of particulate matter and other harmful pollutants. Living near roads is linked to an increased risk of health issues such as cardiovascular conditions. Additionally research has highlighted the phenomenon known as the "street canyon" effect in cities, where tall buildings lining streets trap pollutants at ground level leading to heightened exposure for pedestrians and residents. For instance (Rakowska et al., 2014) . Discovered that street canyon effects in settings can significantly impact air quality along roadways and increase pedestrian exposure to pollutants.

In conclusion, transportation is a key factor in urban air quality degradation with vehicle emissions significantly contributing to PM pollution. The type of pollutants traffic volume and proximity to roads all influence the level of air pollution, affecting the health and well-being of urban populations. Addressing transportation-related air pollution requires integrated approaches including cleaner vehicle technologies, traffic management, and urban planning strategies to reduce exposure and improve air quality.

d) Heating Systems

The effects of heating systems, on particulate matter (PM) levels require an examination of how heating techniques influence air quality, particularly regarding $PM_{2.5}$ and PM_{10} particles. These particles are worrisome because they can easily enter the system.

Wood-burning stoves are known for releasing levels of PM emissions $PM_{2.5}$. When wood burns in these stoves it produces an amount of particulate matter that can negatively impact air quality indoors and outdoors. The kind of wood being burned the temperature at which it burns and how efficient the stove is all influence the quantity and nature of PM released(Cichowicz & Dobrzański, 2021).

Gas furnaces are often seen as more friendly than wood-burning stoves but they still release harmful pollutants. Nitrogen dioxide and carbon monoxide are emissions from gas furnaces. When released into the atmosphere these gases can combine to create secondary particulate matter adding to the levels of particulate matter, in the environment (Cichowicz & Dobrzański, 2021).

Electric Heaters: Many people see heating as an option since it doesn't release combustion-related emissions directly. However, it's important to think about where the electricity comes from. If its produced using fossil fuels like coal or natural gas electric heating can indirectly add to PM levels due to the emissions from power generation (Cichowicz & Dobrzański, 2021).

Seasonal Variations: During seasons the amount of particulate matter released from heating systems can change noticeably. When its colder there is use of heating systems resulting in increased emissions of particulate matter. Winter weather conditions, like temperature inversions, can make the situation worse by trapping pollutants near the ground and stopping them from spreading out. This causes levels of particulate matter in the air in regions where wood and coal are popular choices, for heating purposes(Cichowicz & Dobrzański, 2021).

Studies comparing areas have shown that the type of heating systems used has an impact on air pollution levels. Cities relying on efficient heating methods such as coal and biomass tend to have higher concentrations of particulate matter (PM). These studies emphasize the need to switch to heating options to reduce air pollution. For example switching to gas, electricity or district heating can lower PM emissions. Moreover implementing policies and urban planning strategies that prioritize heating infrastructure can greatly improve air quality and public health in these areas (Kliucininkas et al., 2014). From studying the case examples it's evident that the ways heating is managed during seasons and the specific heating systems in place play roles in affecting particulate matter levels in city settings.

2.7 International Standards and Policies in Hungary of PM_{10} and $PM_{2.5}$

The EPA sets National Ambient Air Quality Standards (NAAQS) with a primary (health-based) standard for $PM_{2.5}$ at 15µg/m³ annually and 35 µg/m³ over 24 hours and PM_{10} at 50 µg/m³ annually and 150 µg/m³ over 24 hours (Us Epa, 2016) in Table 2

The World Health Organization (WHO**)** has set forth recommendations to reduce the health risks linked to air pollution. According to the WHO Air Quality Guidelines (AQGs) it is advised to maintain a $PM_{2.5}$ concentration below 5 micrograms per cubic meter and a PM_{10} concentration below 15 micrograms per cubic meter. Revised in 2021 these guidelines aim to safeguard health by establishing thresholds for air pollutants with the $PM_{2.5}$ limit being reduced from 10 µg/m³ to 5 µg/m³ in Table 1 . This standard is stricter than the European Union's limit of 25 µg/m³ Table 2. Although these guidelines are based on research they are not legally binding; rather they serve as reference points for countries in formulating and improving their air quality policies. To address the challenges faced by regions with pollution levels the WHO has introduced targets for $PM_{2.5}$ and PM_{10} facilitating a gradual decrease in pollution levels. This step-by-step approach helps countries progressively mitigate the health risks associated with air pollution and move closer to meet the WHO air quality standards (de la Salud, Organization, & Health, 2021).

Table 1: WHO guideline for Particulate Matter ($PM_{2.5}$ and PM_{10})

Particle pollution(PM)	Averaging time	Interim target				AQG level
		I	II	III	VI	
$PM_{2.5}$	Annual	35 µg/m³	25 µg/m³	15 µg/m³	10 µg/m³	5 µg/m³
	24 hour	75 µg/m³	50 µg/m³	37.5 µg/m³	25 µg/m³	15 µg/m³
PM_{10}	Annual	70 µg/m³	50 µg/m³	30 µg/m³	20 µg/m³	15 µg/m³
	24 hour	150 µg/m³	100 µg/m³	75 µg/m³	50 µg/m³	45 µg/m³

EU Ambient Air Quality Directives (AAQDs): The EU's Air Quality Directive prescribes limit values for PM_{10} at 40 µg/m³ annually and 50 µg/m³ over 24 hours and for $PM_{2.5}$ at 25 µg/m³ annually on EU Directive No 2008/50/EC *in* Table 2. EU law mandates binding air quality standards including limits for PM_{10} and other pollutants. Member states including Hungary, must comply with these standards or face financial sanctions on EU Directive No 2008/50/EC.

Table 2: Table compares standards of PM_{10} and $PM_{2.5}$ (EPA, WHO, EU, Hungary)

Institution	Particle pollution (PM)	Averaging Time	limit value	Note
EPA	PM_{10}	24 hour	150 µg/m³	Not to be exceeded more than once per year on average over a 3 year period
		Annual	50 µg/m³	Annual arithmetic mean, averaged over 3 years
	$PM_{2.5}$	24 hour	35 µg/m³	98th percentile, averaged over 3 years
		Annual	15 µg/m³	Annual arithmetic mean, averaged over 3 years
WHO	PM_{10}	24 hour	45 µg/m³	
		Annual	15 µg/m³	
	$PM_{2.5}$	24 hour	15 µg/m³	
		Annual	5 µg/m³	

EU	PM_{10}	24 hour	50 $\mu g/m^3$	not to be exceeded more than 35 times a calendar year
		Annual	40 $\mu g/m^3$	
	$PM_{2.5}$	24 hour	NOT SPECIFIED	
		Annual	25 $\mu g/m^3$	
Hungary	PM_{10}	24 hour	50 $\mu g/m^3$	not to be exceeded more than 35 times a calendar year
		Annual	40 $\mu g/m^3$	
	$PM_{2.5}$	24 hour	NOT SPECIFIED	
		Annual	25 $\mu g/m^3$	

Hungary follows the air quality standards set by the European Union to safeguard health and the environment. Decree No. 4 of 2011 establishes limits for PM_{10} and $PM_{2.5}$ pollutants with measures in place to monitor and enhance air quality (Fao, n.d

). The country is implementing initiatives including emission standards for vehicles and industries promoting cleaner heating methods, and transitioning towards renewable energy sources in industry and transport. Hungary plans to ban the sale of petrol, diesel, and hybrid cars by 2028 while encouraging vehicles and improving public transportation. Efforts are also underway to address household air pollution issues by prohibiting waste burning and promoting heating practices.

Despite these measures Hungary has faced challenges such as exceeding the EU's pollution limits for PM_{10} leading to infringement proceedings by the EU. The country is committed to reducing air pollution and greenhouse gas emissions, aligning with the EU's National Emissions Reduction Commitments and the European Green Deal. However, critiques point to the need for more effective implementation and enforcement of these laws to fully meet air quality standards and environmental goals (Zamfir, Croitoru, Burlacioiu, & Dobrin, 2022).

Despite these efforts Hungary has encountered challenges like exceeding EU pollution limits for PM_{10} resulting in infringement proceedings by the EU. The country remains committed to reducing air pollution levels and greenhouse gas emissions in alignment with EU directives such as National Emissions Reduction Commitments and the European Green Deal. Critics argue that there is a necessity, for execution and enforcement of these regulations to effectively achieve air quality benchmarks and environmental objectives.

In summary, while Hungary has established comprehensive policies and standards to mitigate air pollution, especially PM_{10} and $PM_{2.5}$, the nation continues to face implementation challenges in fully adhering to these stringent environmental protections.

2.8 Effects of PM in Global Context and EU

Particles in the air also known as particulate matter (PM) pose an environmental health concern on a scale impacting both human well-being and the balance of ecosystems. $PM_{2.5}$ and PM_{10} (particles measuring 2.5 and 10 micrometers in diameter) have the ability to enter deeply into our system and bloodstream leading to various health issues. Globally, exposure to $PM_{2.5}$ has been found to be associated with rates of death and illness impacting the respiratory systems and leading to conditions like stroke, heart disease, lung cancer, COPD and respiratory infections. Research suggests that millions of deaths happen each year due to $PM_{2.5}$ exposure with a significant impact seen in areas such as Asia, Africa and the Middle East where there is a dense population and substantial pollution sources overlap(Janssen, Fischer, Marra, Ameling, & Cassee, 2013) .

In the context of Europe pollution from particulate matter (PM) poses a concern for health mainly due to industrial emissions, vehicle exhaust, home heating, and agricultural practices. The European Union (EU) has put in place air quality standards through the Ambient Air Quality Directive to reduce the impacts of air pollutants like PM. These guidelines aim to safeguard health and the environment by setting limits on the allowable concentrations of key pollutants. Despite these regulations many EU nations encounter difficulties in meeting and sustaining these air quality standards in regions where sources of pollution are dense. According to the European Environment Agency a significant portion of residents in EU countries are exposed to PM levels that surpass both EU and World Health Organization (WHO) recommendations posing health risks that call for measures to enhance air quality (Sicard, Agathokleous, De Marco, Paoletti, & Calatayud, 2021).

The European Union tackles PM pollution by monitoring air quality controlling emissions from sources and enacting measures to decrease emissions, from transportation, industry, and farming. Moreover, they promote awareness. Encourage behavioral shifts to decrease individual exposure and help enhance overall air quality.

2.9 Key Findings from Previous Case Studies

PM pollution poses a concern in Hungary impacting both the air quality and public health. Past studies have explored facets of PM pollution, such as its origins, levels of concentration changes over time, and effects on health. The summary of the key findings from these studies is summarized in Table 3.

Table 3: The key finding from Previous case studies

Name of research	Key findings	
Long-term Characterization of Urban PM_{10} in Hungary	The study in Hungary, conducted from 2007-2017, examined high PM_{10} concentrations in urban areas of Budapest, Miskolc, and Pécs. The study found that while annual average PM_{10} concentrations in urban areas are below 40 µg/m³, daily concentrations exceed EU guidelines. The study used the Kolmogorov-Zurbenko filter to differentiate between meteorological and emission-related trends.	(Ferenczi et al., 2021)

Characterization of Aerosol Pollution in Two Hungarian Cities in Winter 2009–2010	The study in Hungary was caried out during the winter of 2009-2010 and examined the air pollution levels in Budapest and Debrecen. A crucial finding was the frequent exceedance of WHO recommended $PM_{2.5}$ limits, with 73% of days in Budapest and 50% in Debrecen surpassing these levels, indicating substantial fine particulate pollution. The study also identified pollution sources, including traffic, biomass burning, and secondary sulfate, which significantly contribute to $PM_{2.5}$ levels.	(Furu et al., 2022)
Changes in chemical composition and oxidative potential of urban $PM_{2.5}$ between 2010 and 2013 in Hungary	The study carried out in Budapest Hungary, specifically at an urban site affected by road traffic from June 2010 to May 2013. The average $PM_{2.5}$ concentration was just below the EU limit, with significant seasonal variations, higher in winter due to factors like residential heating. While no clear trend in annual concentrations was observed, the study found that the oxidative potential of $PM_{2.5}$ was mainly associated with traffic-related trace elements, indicating a strong link between vehicular emissions and particulate pollution's ability to cause oxidative stress.	(Szigeti et al., 2015)

Ambient concentrations of PM_{10}, PM_{10}-bound polycyclic aromatic hydrocarbons and heavy metals in an urban site of Győr, Hungary	The study was conducted in Győr, a city in northwest Hungary, from 2008 to 2012. The study found that PM_{10} concentrations varied between 7.90 to 119.14 µg/m³, with an average of 34.94 µg/m³ over the study period of 2008–2012. The total PAHs and heavy metals in PM_{10} were found to be relatively low, comprising 0.04% and 0.06% of the total PM_{10} mass, respectively. The study observed higher concentrations of PM_{10} and PAHs during the heating seasons, indicating the influence of local heating (winter) on air quality.	(Szabó, Nagy, & Erdős, 2015 2015 2015)
Contributions to cities' ambient particulate matter (PM): A systematic review of local source contributions at global level	The review analyzed studies from 51 countries, providing a global perspective on urban PM sources. The study found that globally, 25% of urban ambient air pollution from $PM_{2.5}$ is contributed by traffic, 15% by industrial activities, 20% by domestic fuel burning, 22% from unspecified sources of human origin, and 18% from natural dust and salt.	(Karagulian et al., 2015)
PM_{10} and $PM_{2.5}$ concentrations in Central and Eastern Europe: results from the Cesar study	The study was conducted in 25 study areas across Bulgaria, Czech Republic, Hungary, Poland, Romania, and the Slovak Republic. The study revealed a significant increase in PM_{10} and $PM_{2.5}$ concentrations across Bulgaria and Poland, with the highest levels in Bulgaria and Poland and the lowest in the Slovak Republic, indicating that local heating during winter is a significant source of particulate pollution.	(Houthuijs et al., 2001)

In conclusion, High levels of particulate matter (PM) pollution in Hungary present public health challenges especially in urban areas. While past research has established an understanding of the extent and effects of PM pollution there is still a call for more studies to assess the success of mitigation tactics and grasp the lasting health impacts linked to PM exposure. Ongoing research should strive to offer an understanding of how PM pollution evolves, aiding in the development of policies and actions to enhance air quality and public health .

3. Materials and methods

3.1 Study area

This study focuses on particulate matter (PM_{10} and $PM_{2.5}$) concentrations in the city of Gödöllő, Hungary. Gödöllő is a picturesque town located 30 km northeast of Budapest, nestled in the Pest County along the Rákos stream. It enjoys the convenience of direct access to the M3 highway, the new M31 road, and Main Road No. 3, along with a major railway line connecting Budapest to Miskolc. Gödöllő is part of the expansive Great Hungarian Plain, featuring flat to gently rolling landscapes.

Gödöllő's green, forest-rich environment, historically known for royal hunting grounds, encompasses about a hundred square kilometers of forests with a significant portion managed by the town. Notably, the town is free of air-polluting industries. The administrative domain of Gödöllő spans 61.93 square kilometers in Figure 2, of which 16 square kilometers are an Urban area shown in Figure 3 and a population of 32 625 (POPULATION, 2024)

Figure 5: Gödöllő Boundary

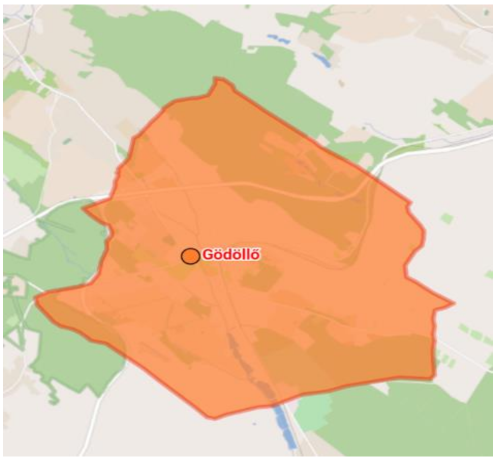
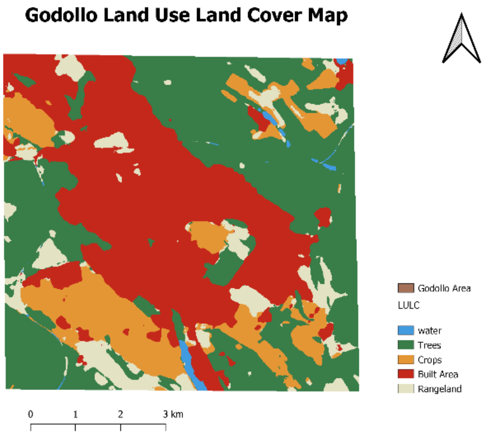


Figure 6: Gödöllő land use land cover map



3.2 Data collection

Daily particulate matter (PM) samples, specifically PM10 and PM2.5 concentrations, were collected from February 17th to May 1st 2023, during the transition from winter to spring season. Sampling was conducted over 24 hours at two distinct locations in Gödöllő.

Sensor A (outside city center) was located 1.5 km away from Sensor B in Figure 5 (latitude 47.612074 and longitude 19.347801) 370 meters from the nearest motorway. This area predominantly uses traditional wood for heating contrasting with the central heating system near Sensor B.

Sensor B (city center) is positioned centrally in downtown Gödöllő (latitude 47.5988190 and longitude 19.3443982. This sensor was positioned near a supermarket, a church, and a central heating system as shown by the yellow pinpoint in Figure 6.

Parameters recorded in the research were the levels of PM_{10} and $PM_{2.5}$ concentrations which were measured in micrograms per cubic meter ($\mu g/m^3$). Temperature, humidity, and air pressure readings were gathered at both locations to better understand how environmental factors impact PM concentrations. Wind speed data was collected from the website met.hu. This thorough data collection method enables an examination of how particulate matter dynamics are shaped by urban and suburban environments diverse heating systems and local infrastructure.

Figure 7: Two location of sensors

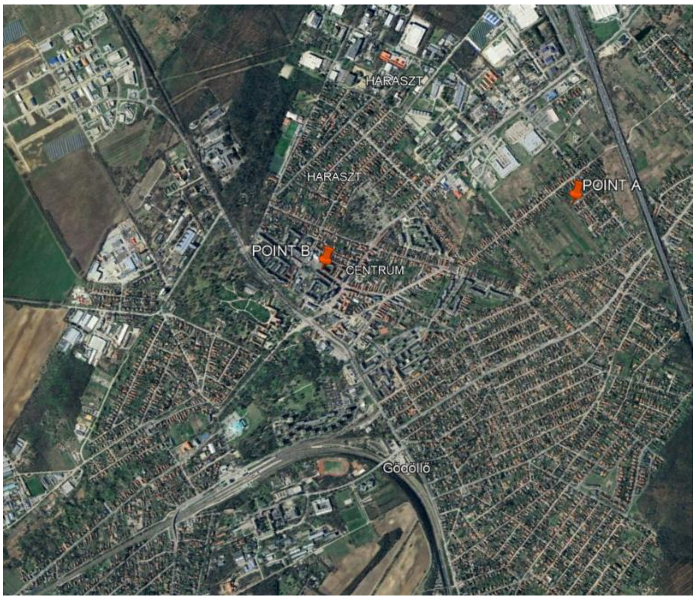


Figure 8: Sensor located outside of the city center

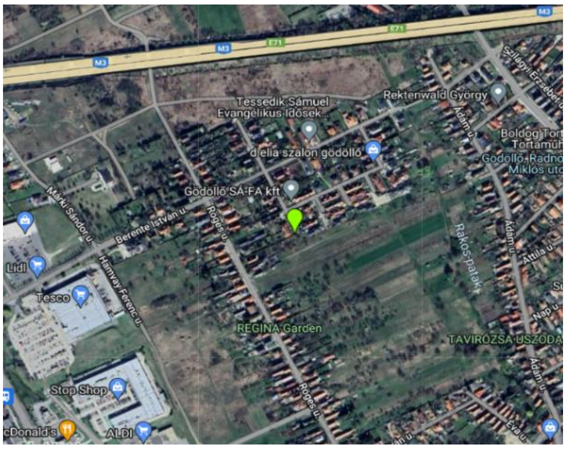
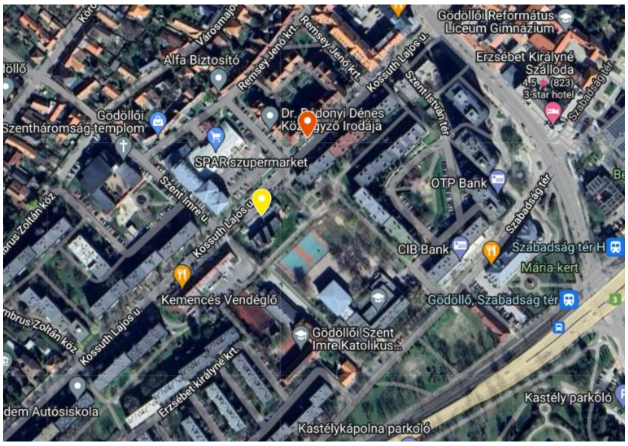


Figure 9: Sensor located at the center



3.3 Data Sources

To record the PM concentrations the Honeywell HPMA115S a laser-based sensor was used which is shown in Figure 8. With a measurement range spanning from 0 to 1000 µg/m³ it can function effectively in humidity levels ranging from 0 to 95% RH and temperatures between 10℃ to 50°C. This sensor plays a role in monitoring air quality by offering real-time data outputs and being adaptable for use in both stationary settings across various environmental conditions (Csongor Báthory, 2020)

The sensor was placed about 1.5 to 2 meters above ground level to collect data to the area where people breathe. The sensor runs on a DC power source and communicates data through an interface. It was linked to a microcontroller for recording data and in depth examination. The setup process included adjusting the data output frequency and calibration settings either using Honeywell's software or by sending commands through the connection (Csongor Báthory, 2020)

To ensure precision the sensor underwent calibration with advanced reference devices. This crucial process helps address any inaccuracies or discrepancies, in the sensors readings in situations relating to regulations or health concerns. Continuous data logging was carried out with time stamps utilizing a data logger connected to the microcontroller. This configuration enabled the real-time tracking and assessment of PM levels.

The sensor data was analyzed using software tools for tasks, like time series analysis and correlation studies to understand changes in particulate matter trends. An interactive Grafana dashboard was set up to display real-time monitoring data on air quality conditions. The information is organized in a database by website and app developers initially validated manually but can be automated through learning from observations (Figure 7). Verified data is then translated into a color scale (Csongor Báthory, 2020). The advanced configuration of the Honeywell HPMA115S0 sensor allows for thorough monitoring of air quality offering information in Gödöllő.

Figure 10: How to receive the data

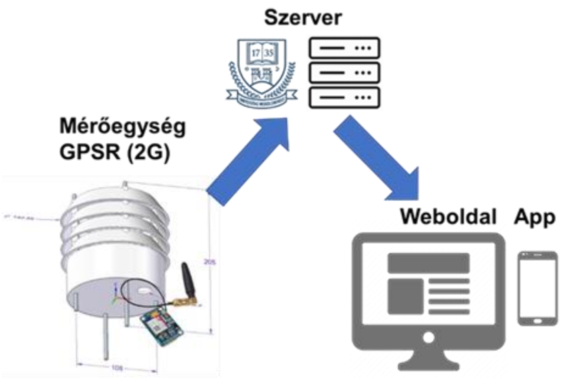


Figure 11: Honeywell HPMA115S0 sensor

wind speed data obtained from the Hungarian Meteorological Service, which can be accessed on their website met.hu. This organization is well-regarded for its thorough collection of data. By following data collection standards the Hungarian Meteorological Service guarantees the precision and trustworthiness of its data.

The wind speed information gathered for this research was logged hourly. This frequent data recording enables an examination of how wind speeds vary throughout the day and their potential influence on levels of particulate matter. The data collection period covers the entirety of 2022 allowing for an analysis of changes in wind speed and their impact on the dispersion of particulate matter. It is crucial to collect data across all seasons to draw conclusions about the relationship between wind speed and particulate matter levels, throughout the year.

3.4 Data analysis

Throughout each experiment, measurements were taken every 102 seconds and recorded in an in Excel sheet. The results show the average PM_{10} and $PM_{2.5}$ concentrations in comparison to temperature, humidity, and pressure in each test.

Basic Statistics: Employed to summarize the central tendencies and dispersion of environmental data and PM levels. Such as minimum, maximum, standard deviation, and average for 74-day of data collected by the formula below (Agarwal, 2006):

The minimum is the smallest value in a dataset. There is no complex formula for this. You just take the smallest value in the list of data points:

$$\text{Minimum}=\min(x_1,x_2,\ldots,x_n) \tag{1}$$

The maximum is the largest value in a dataset. Like the minimum, this is a straightforward calculation:

$$\text{Maximum}=\max(x_1,x_2,\ldots,x_n) \tag{2}$$

Standard deviation is a measure of the dispersion or spread of a dataset. It indicates how much the individual data points deviate from the mean. The formula for standard deviation is:

$$\sigma = \sqrt{\frac{\sum (xi-\mu)^2}{n}} \tag{3}$$

Where: σ is the standard deviation.

xi represents each data point.

μ is the mean of the data.

n is the number of data points.

The average (or mean) is the central tendency of a dataset. It represents the sum of all data points divided by the number of points:

$$\mu = \frac{\sum_{i=1}^{n} xi}{n} \tag{4}$$

Where: μ is the average.

Xi Represents each data point.

n Is the number of data points.

Visual Data Representations: Graphs and charts were created to visually depict the relationships and trends within the collected data.

a) For Analysis of temperature, humidity, pressure, and correlations with PM concentrations

We used Correlation Analysis We chose Pearson correlation analysis to examine the connection, between particulate matter (PM) levels and various environmental factors like temperature, humidity, and air pressure. This method allows us to showcase the strength of a linear relationship between two distributed variables. The coefficients range from -1, to +1, where: A correlation of 1 implies a perfect positive linear relationship.

A correlation of -1 implies a perfect negative linear relationship.

A correlation of 0 implies no linear relationship.

To create a correlation matrix, you can compute correlations among all pairs of variables. If you have n variables the correlation matrix is an n×n symmetric matrix, where each element r_{ij} represents the correlation between the i and j the variables. The diagonal elements are always 1 because any variable is perfectly correlated with itself (Emerson, 2015).

Mathematically, the Pearson correlation coefficient between two variables X and Y is given by:

$$rij = \frac{n\sum(x.y)-(\sum x)(\sum y)}{\sqrt{(n.\sum x^2-(\sum x)^2)(n.\sum y^2-(\sum y)^2)}} \tag{5}$$

Where: n is the number of data points

$\sum x\ \ is\ the\ sum\ of\ all\ values\ in\ x$

$\sum y\ \ is\ the\ sum\ of\ all\ values\ in\ y$

$\sum(x.y)$is the sum of the element-wise product of X and y

$\sum x^2 and\ \ \sum Y^2$Are the sum of squares of x and y respectively

For instance, a positive coefficient linking PM concentrations and temperature implies that higher temperatures correspond to increased PM levels whereas a negative coefficient suggests the scenario.

b) For seasonal variations in PM concentrations and the influence of transportation and heating systems.

we used Time Series Analysis to identify trends and patterns in PM concentrations over the selected period. we applied time series analysis to pinpoint when and where particulate matter (PM) levels were highest. By mapping PM data across different times of day(early morning, morning rush, and evening rush) and seasons we aimed to identify specific sources of pollution. During rush hours we checked for increases, in particulate matter (PM) levels to see if traffic had an effect on air quality. We also investigated the correlation between PM levels and the usage of heating systems on colder days. Additionally, we analyzed PM data throughout seasons to understand how weather conditions and seasonal activities such, as using heating systems in winter, influence PM levels. The objective was to establish links, between PM concentrations and their possible origins like heavy traffic or operational heating systems.

c) Analyze Weekdays vs. Weekends

Data Segregation First we categorize your data into two groups; weekdays (Monday, to Friday) and weekends (Saturday and Sunday). This means assigning each data entry to the group based on the day of the week.

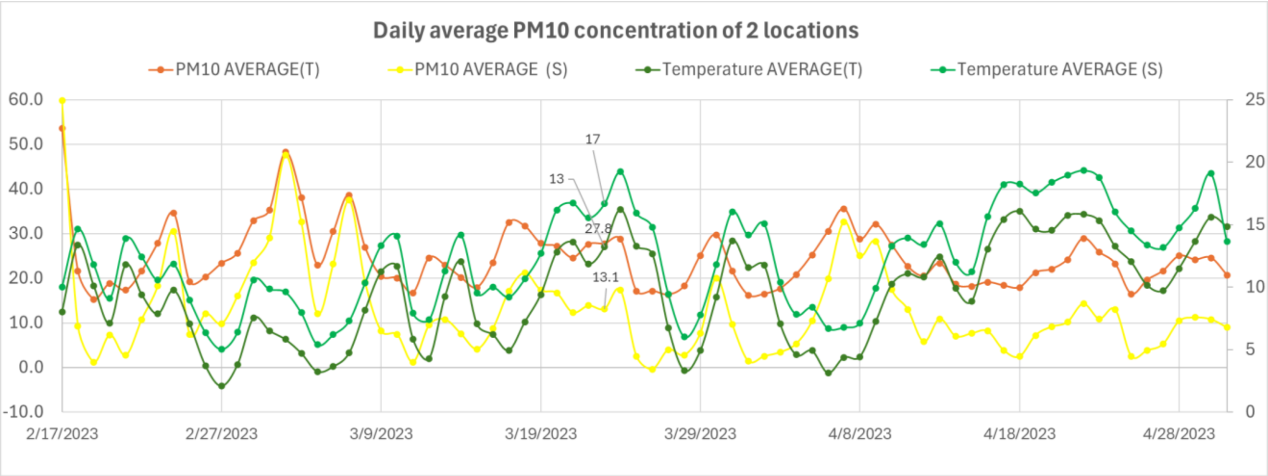
Data Compilation Determine the levels of $PM_{2.5}$ and PM_{10} for each group (weekdays and weekends). This allows you to compare whether particulate matter concentrations tend to be higher during weekdays or weekends.

Examining Relationships with Temperature and Traffic Data Integrate temperature information into the analysis to explore if lower temperatures (indicative of increased heating usage) are linked to PM levels. Furthermore, if there is access to traffic volume data analyze its correlation, with PM levels to evaluate the influence of traffic.

4. Result

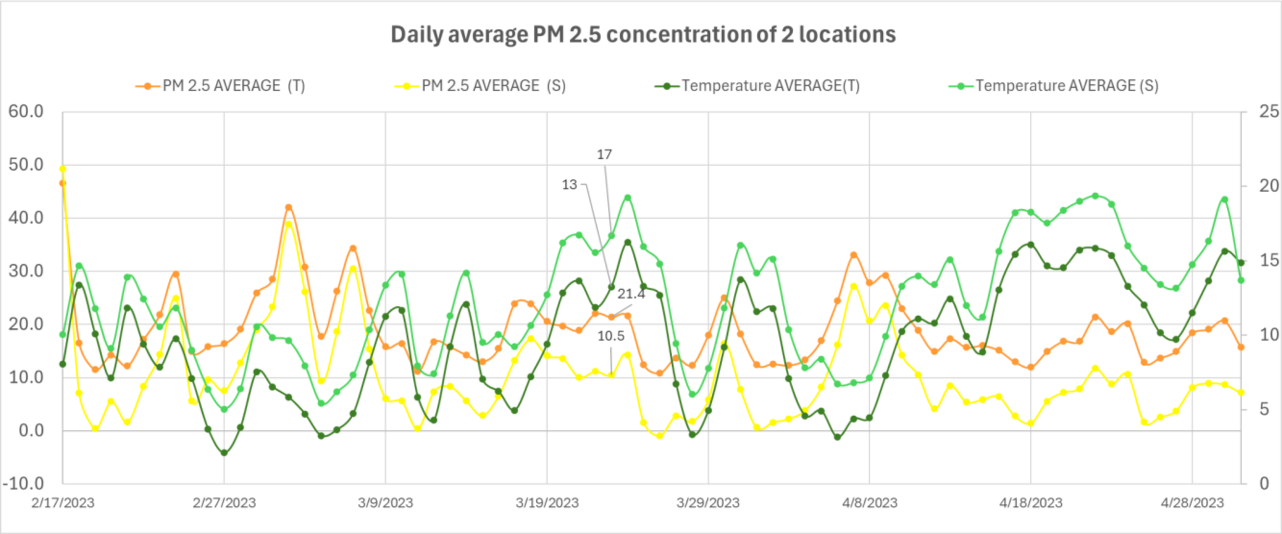
4.1 Comparative analysis of PM_{10} and $PM_{2.5}$ concentrations between the urban center and rural locations

Figure 12:Daily average PM$_{10}$ concentration and temperature of two locations



The graph in Figure 9 shows PM 10 concentrations of the two locations. Central (yellow line) and outside of Central (orange line) have similar patterns. Therefore, the outside of Central has higher concentration than Central (for example, on the 23rd of March the difference of the PM$_{10}$ concentration outside of Central is 13.2 $\mu g/m^3$ and central is 27.8 $\mu g/m^3$) in Figure 9. This difference may stem from the proximity of the sensor near the highway to traffic and the temperature lower than central a known source of PM$_{10}$.

Figure 13: Daily average of PM$_{2.5}$ concentration and temperature of two locations



The graph in Figure 10 shows PM $_{2.5}$ concentrations of the two locations, Central (yellow line) and outside of Central (orange line) have similar patterns, but outside of Central has a higher concentration than Central. we can see that the Central average of PM$_{2.5}$ concentration is

10.39 µg/m³ and the outside of the central average of $PM_{2.5}$ concentration is 19.18µg/m³. This difference may stem from the proximity of the sensor near the highway to the traffic and the temperature lower.

4.2 Analysis of temperature, humidity, pressure, and wind speed correlations with PM concentrations

Pearson correlation analysis provides the following insights into the relationship between $PM_{2.5}$ and PM_{10} concentrations and temperature, atmospheric pressure, and relative humidity. calculated by Equation (5) and we will get the result below

Outside of Central: $PM_{2.5}$ and PM_{10} often move in sync with a relationship (0.97) in Table 3 indicating that their levels tend to rise or fall together due, to various shared factors such as the same common sources.

Additionally, temperature demonstrates a correlation, with both $PM_{2.5}$ and PM_{10} (0.28) Table 3 suggesting that higher temperatures could potentially lower particulate matter levels possibly because of increased atmospheric turbulence and dispersion.

The relationship, between pressure and PM_{10} shows a connection especially with a correlation coefficient of 0.39 for PM_{10} indicating that increased pressure could result in higher levels of particles potentially due to more stable atmospheric conditions that limit their dispersion. On the hand, relative humidity displays a positive correlation with $PM_{2.5}$ (0.25) in Table 3 and an even lower correlation with PM10 hinting at a minor impact on particle concentrations. These natural elements offer insight into how particle levels may fluctuate in response, to weather conditions.

Central: Similar to the location outside of central, $PM_{2.5}$ and PM_{10} have a very high positive correlation (0.99) in Table 4, indicating strong co-variation. The temperature has a negative correlation with $PM_{2.5}$ and PM_{10} (- 0.29) in Table 4, similar to the outside of Central Pressure shows a slight positive correlation with $PM_{2.5}$ and PM_{10} (0.30) in Table 4. Relative humidity has a low positive correlation with $PM_{2.5}$ and PM_{10}.

In both locations, particulate matter $PM_{2.5}$ and PM_{10} are highly correlated with each other and they have similar patterns of correlation with other environmental factors like temperature, atmospheric pressure, and humidity. Temperature tends to be inversely related to particulate matter concentration, while pressure shows a positive correlation. Humidity's correlation with particulate matter is positive but weaker compared to pressure and temperature.

Table 4: Correlation matrix Outside of central

OUTSIDE OF CENTRAL	PM 2.5 Average	PM10 Average	Temperature Average	Pressure Average	Rh Average
PM 2.5 Average	1	0.97	-0.28	0.30	0.25
PM10 Average	0.97	1	-0.29	0.39	0.027
Temperature Average	-0.28	-0.29	1	-0.19	-0.11
Pressure Average	0.30	0.39	-0.19	1	-0.37
Rh Average	0.25	0.03	-0.11	-0.37	1

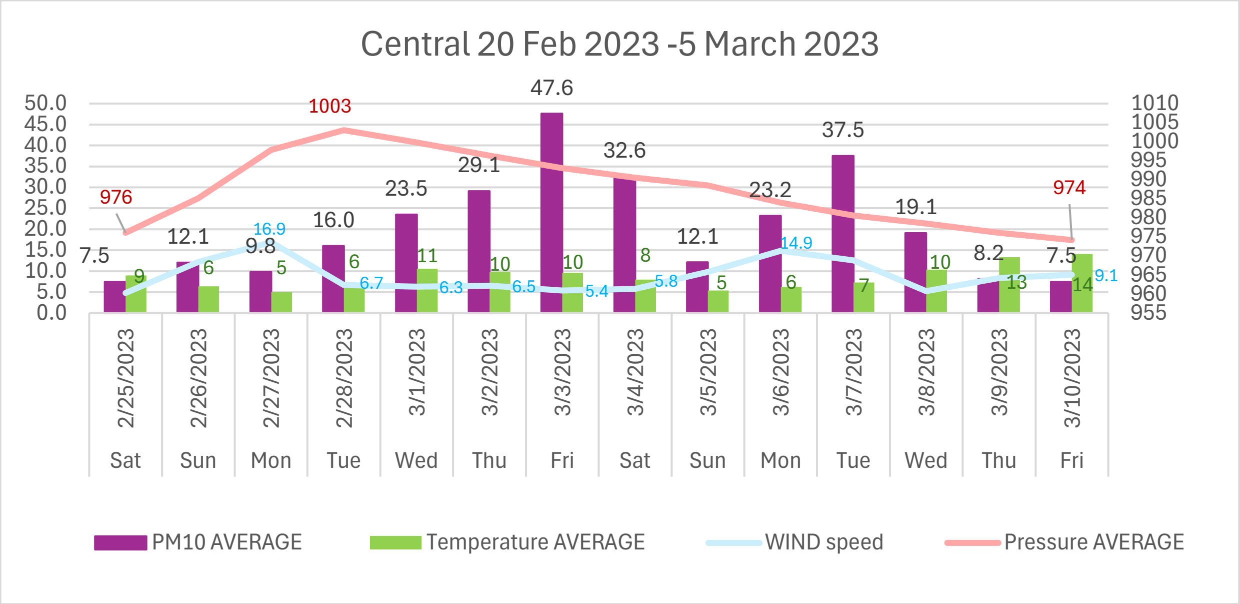
Table 5: Correlation Matrix at the central

CENTRAL	PM 2.5 Average	PM10 Average	Temperature Average	Pressure Average	Rh Average
PM 2.5 Average	1	1.00	-0.29	0.30	0.15
PM10 Average	1	1	-0.29	0.30	0.15
Temperature Average	-0.29	-0.29	1	-0.19	-0.16
Pressure Average	0.30	0.30	-0.19	1	-0.42
Rh Average	0.15	0.15	-0.16	-0.42	1

4.3 Analysis of temperature, pressure, and wind speed correlations with PM concentrations

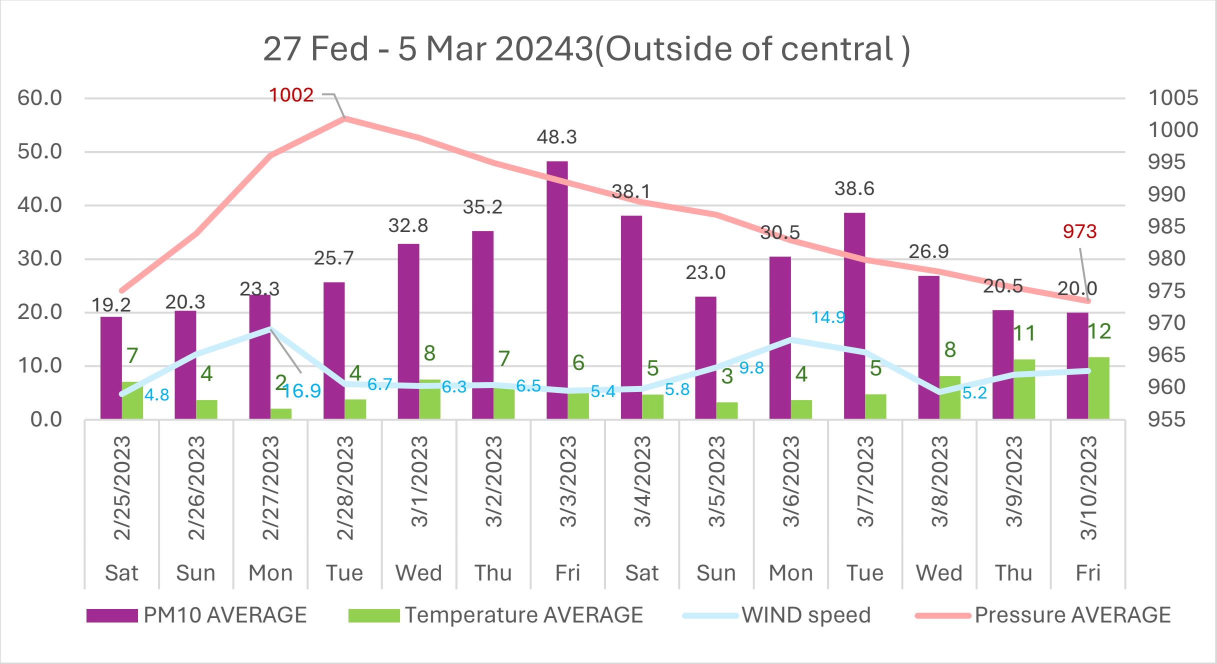
a) PM concentration with air pressure is stable and wind.

Figure 14: PM$_{10}$ concentration with air pressure is stable and weed speed changes at the central



The graph in Figure11 shows that from the 28th of February to the 4th of March atmospheric pressures are highest at approximately 1003 hPa - 990 hPa and during that time the wind speeds are steady ,showing that PM$_{10}$ concentration maximum 47.6 µg/m^3 are higher than 25th- 24th of February in those days because the wind speed is higher than 28th of February to 4th of March even the temperatures in those 3 days are lower. From on 4th to 6th of March you will see that PM10 concentration on 5th of March is decreased from 32.6 µg/m^3 to 12.1 µg/m^3 and increased on 6th of March before the wind speed increased from 5.4 m/s to 14.9 m/s.

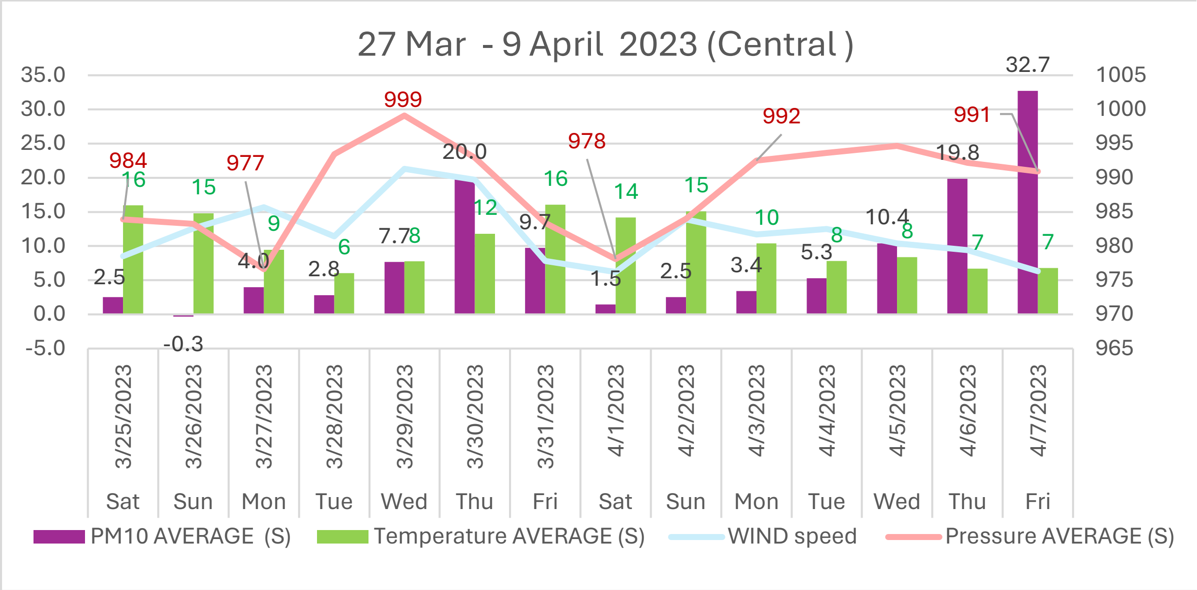
Figure 15: PM$_{10}$ concentration with air pressure is stable and weed speed change at the outside of the central



The graph in Figure12 show, From 25th February to 3rd of March 2023. PM$_{10}$ concentration increases every day 19.2 µg/m³, 20.3 µg/m³,23.3 µg/m³, 25.7 µg/m³, 32.8 µg/m³,35.2 µg/m³, 48.3 µg/m³ respectively , temperatures average 5°C , atmospheric pressure average 992 hPa (maximum 1002 hPa) during 25th February to 3rd of March 2023. From 4th - 6th of March shows that on Sunday 5th of March 2023, PM$_{10}$ concentration decreased from 38.1 µg/m³ to 23.0 µg/m³ and increased on Monday 6th of March because wind speed increased and the Vehicle started work on the week. From 7th – 10th March you will see that PM$_{10}$ concentration decreases day by day from 26.9 µg/m³, 20.5 µg/m³, 20 µg/m³ because of the temperature increases 8°C, 11 °C and 12°C respectively.

b) PM concentration with air pressure unstable

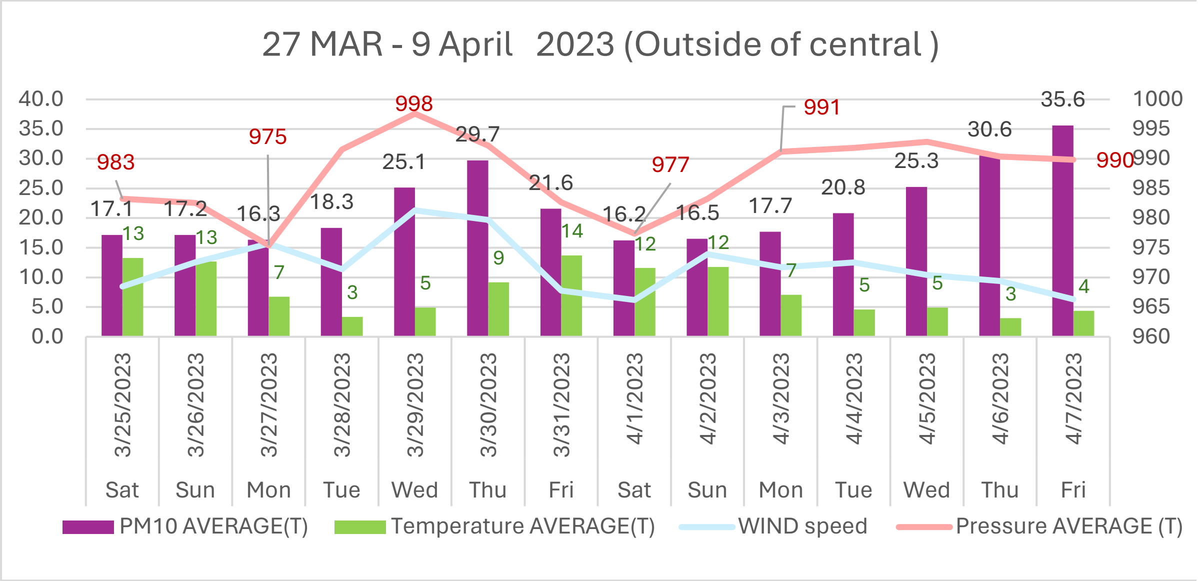
Figure 16: PM$_{10}$ concentration with air pressure (unstable) and weed speed change at the central



The graph in Figure13 show it fluctuates because of atmospheric pressure is unstable maximum pressure is 999 hPa and the minimum is 977 hPa. On high-pressure days especially if there is an anticyclone (a high-pressure system with clockwise circulation in the Northern Hemisphere) wind speeds can be lower reducing the dispersal of air pollutants and leading to their accumulation. On low-pressure days, which are often associated with cyclonic systems wind speeds are generally higher improving the ventilation and dispersal of pollutants.

The graph in Figure13 shows From the 28th of March to the 7th of April PM concentration increased and decreased influenced by atmospheric pressure. On 28th to 30th of March PM concentration increased from 2.8 µg/m^3,7.7 µg/m^3,20 µg/m^3 respectively and decrease from 31st to 1st of April 9.7 µg/m^3 and 1.5 µg/m^3 respectively and increase from 2nd of April to 7th of April 3.4 µg/m^3,5.3 µg/m^3, 10.4 µg/m^3, 19.8 µg/m, 33.7 µg/m^3 respectively. On 7th of April has the highest PM10 concentration 32.7 µg/m^3. Even have the same temperature of 7℃ as yesterday, on the 6th of April because the is Good Friday and far from the sensor 100 m show in Figure 6 is a church ,people went there why on 7th April PM concentration was higher than 12,9 µg/m^3 on the 6th of April.

Figure 17 :PM$_{10}$ concentration with air pressure (unstable) and weed speed change outside of the central

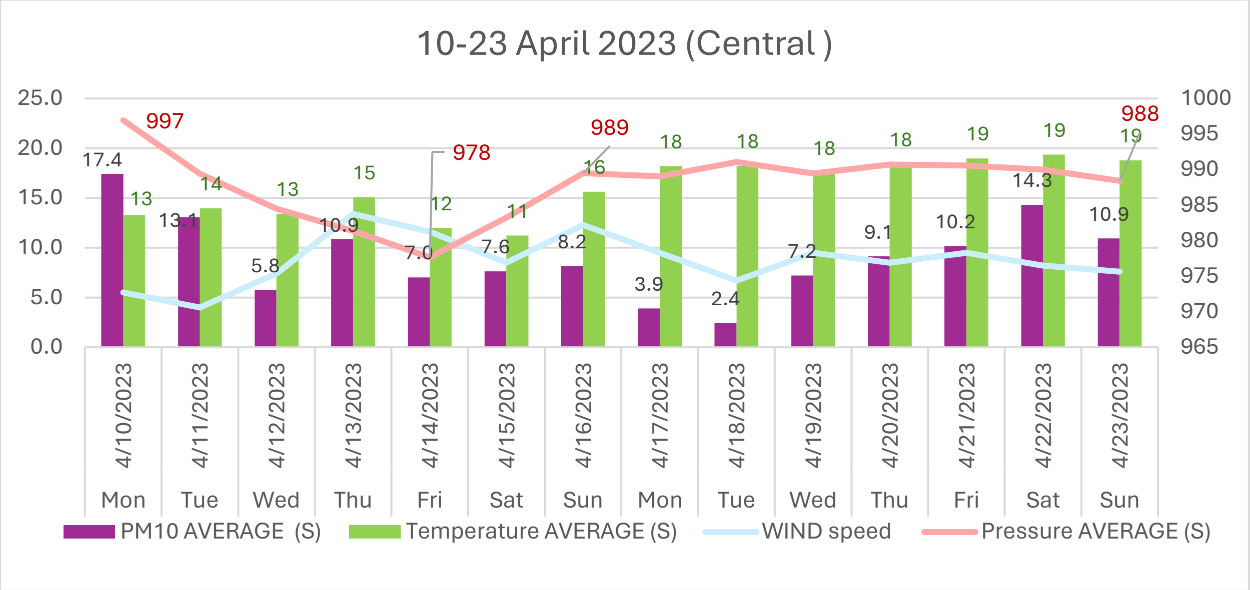


The graph in Figure14 show is fluctuates because of atmospheric pressures are unstable, the maximum of pressure is 998 hPa and the minimum is 975 hPa, from 25th to 26th March PM$_{10}$ concentration the steadiness is 17.1µg/m^{3}And 17.2µg/m^3 because of pressure and temperatures are steadiness, they are the same pressure 983 hPa and temperature 13℃. The graph in Figure 14) show From the 27th of March to the 1st of April, PM$_{10}$ concentration fluctuates with air pressure we can see in this graph. PM$_{10}$ concentration increased From 27th-30th of March 16.3 µg/m^3, 18.3 µg/m^3, 25.1 µg/m^3,29.7 µg/m^3 respectively and depending from 31st of March to 1st of April 21.6 µg/m^3,21.6 µg/m^3 respectively pressure also increases and decrease in the same time, on 4th of April PM$_{10}$ are increased and pressure also increased, during this to week on 7th of March has most PM concentration because is a Good Friday

c) PM concentration with the high temperature in period months on central

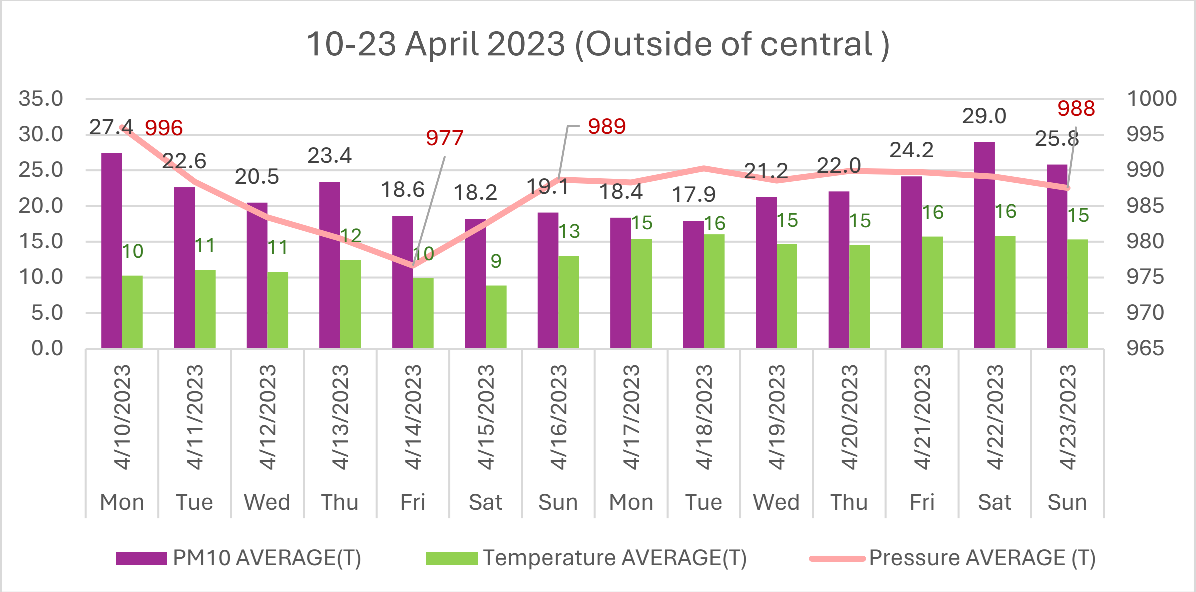
Temperature and PM Concentration: Higher temperatures can sometimes lead to increased chemical reactions that form secondary particulate matter. However, the relationship can be complex, depending on other factors like sunlight, humidity, and the presence of precursor chemicals.

Figure 18: PM_{10} concentration cause of temperature at the *central*



The graph (Figure15) shows, From 10th – 23rd of April temperatures are increasing these days and we had a change of season from winter to spring. and pressure is stable average 989 hPa, During these 2 weeks the highest temperature and PM10 concentration are decreased.PM_{10} concentration average is 9.2 µg/m³ and the maximum was 17.4 µg/m³. On the 10th of April temperature was 13 ℃ and the PM_{10} concentration was 17.4 µg/m³ on the 11th of April .On 11th April PM_{10} concentration is decreased from 17.4 µg/m³ to 13.1 µg/m³ because of the temperatures increase from 13℃ to 14 ℃ and PM concentration will always decrease if temperatures are higher and if someday have atmospheric pressure are lower that means weather fronts that can bring rain, storms, and increased wind speeds. Precipitation can remove pollutants from the air through a process called "wet deposition" where pollutants are captured by raindrops and removed from the atmosphere. Will decrease PM_{10} concentration more like on the 12th of April it has wind during that day because the pressure is lower than before from 997 hPa to 985 hPa decreases more than thrice times compared to the 10th of April even though they are the same temperature ,from 17th -23rd April on weekend have more concentration than weekday 12.6 µg/m³ and 6.6 µg/m³ respectively.

Figure 19:PM_{10} concentration cause of temperature at outside of the central

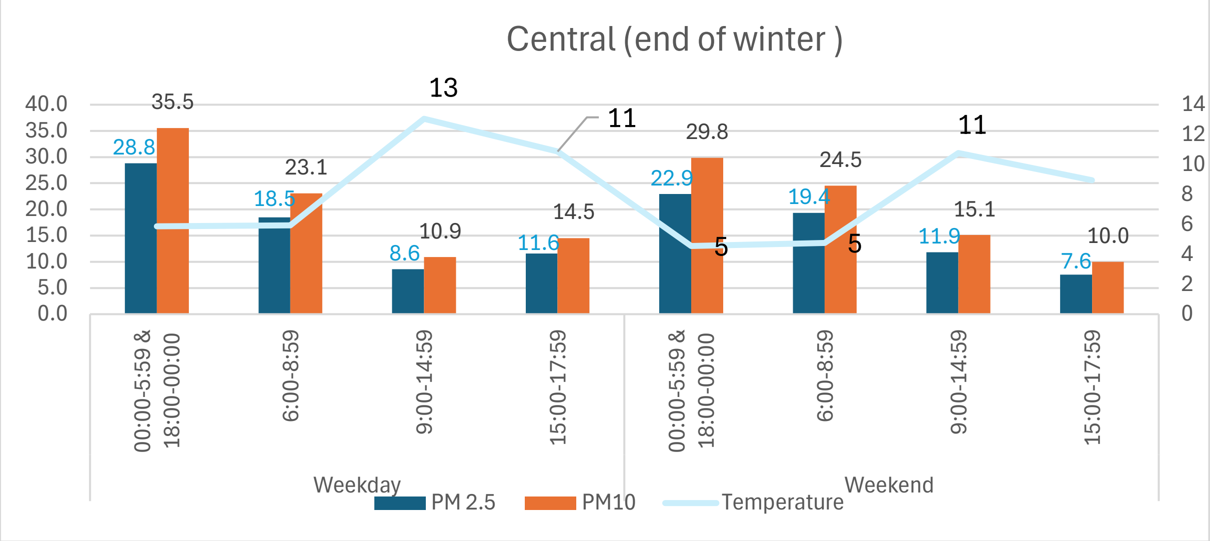


This graph in Figure16 shows that PM concentration doesn't so change much from each other average PM composition and temperature is 22 °C and 13°C maximum 29 °C and 16°C. On the 10th of April and 14th of April they have the same temperature of 10°C but different PM_{10} concentrations 27.4 μg/m³and 18.6 μg/m³ respectively because the pressures are decreased from 10th of April to 14th of April 996 hPa and 976 hPa low-pressure days, which are often associated with cyclonic systems wind speeds are generally higher improving the ventilation and dispersal of pollutants. From 17th – 23rd April weekends and weekdays have the same PM_{10} concentration average of 21 μg/m³.

4.3 Seasonal variations in PM concentrations and the influence of transportation and heating systems

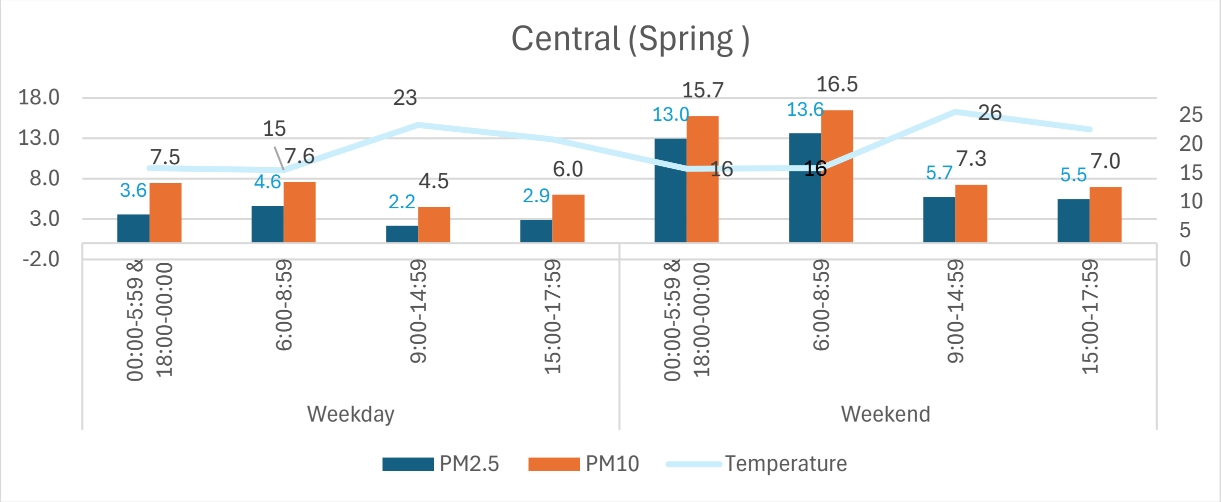
a) Sensor at Central

Figure17: PM concentration on the end of winter at the central



PM$_{2.5}$ and PM$_{10}$ Concentrations during the End of Winter: The graph in Figure 17 shows that PM$_{2.5}$ and PM$_{10}$ levels are generally higher during weekdays than on weekends across all selected time slots. This pattern suggests increased particulate matter emissions during weekdays, likely due to higher traffic and possible heating activities. Early Morning (00:00-5:59) and late night (18:00 -00:00) are Notably highest on weekdays and weekends, possibly due to heating systems. From 6:00-18:00 during the weekdays, from 9:00 - 14:59 Particulate matter (PM) concentrations are lower than rush hours (6:00-8:59) and (15:00-17:59) Both periods on show increased PM$_{2.5}$ and PM$_{10}$ levels on weekdays which a peak traffic times as people commute to and from work.

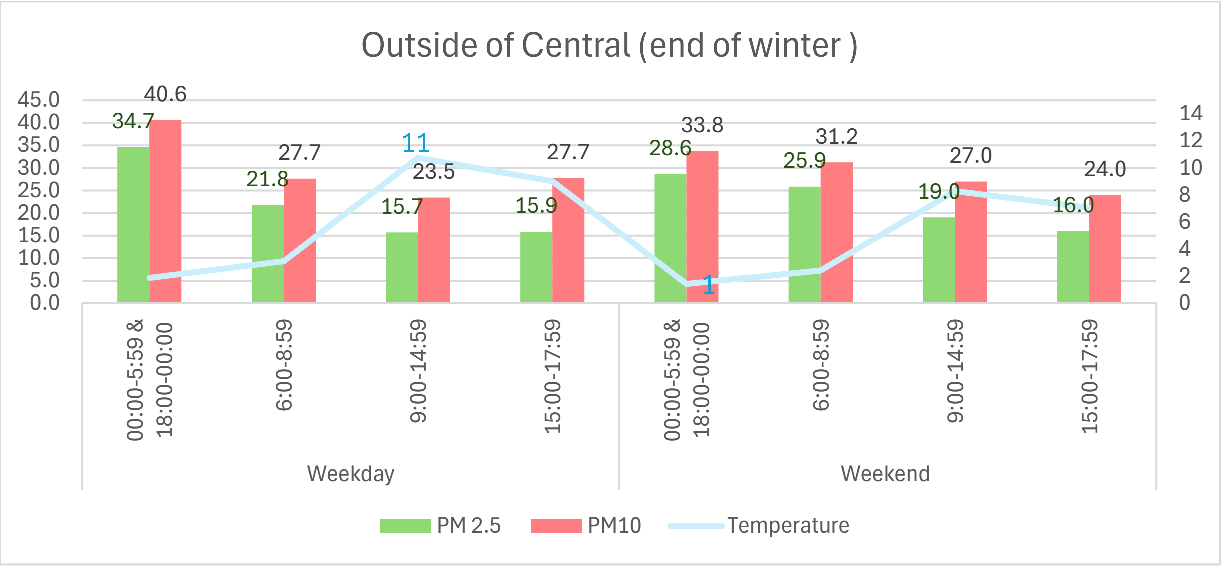
Figure 18:PM Concentration on spring at the central



$PM_{2.5}$ and PM_{10} Concentrations during the Spring: The graph in Figure 18 shows that $PM_{2.5}$ and PM_{10} levels are generally lower during weekdays than weekends because in spring temperature is higher than the end of winter average of 18.5℃ and 7℃ respectively. The graph in Figure 18 shows that PM concentrations are higher in the morning - late at night on the weekend because the temperature at that time is lower (minimum 12℃). From 9:00-17:59 $PM_{2.5}$ and PM_{10} concentrations are decreased because people do activities outside.

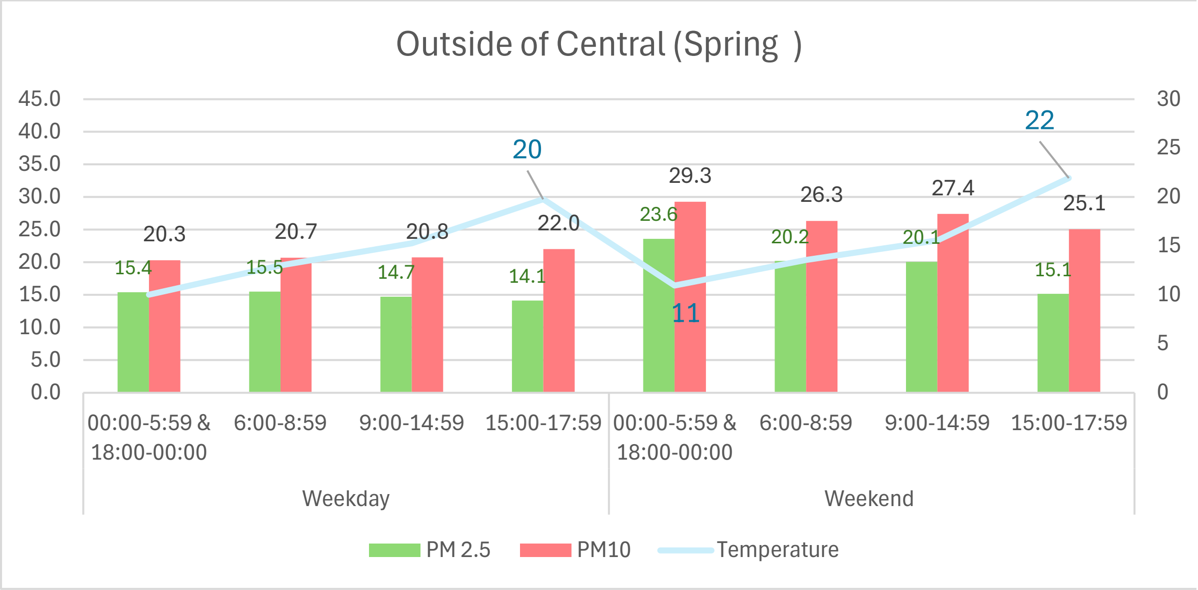
a) Sensor outside of the central

Figure 19: PM concentration on the end of winter at outside of the central



$PM_{2.5}$ and PM_{10} Concentrations during the End of Winter: PM Concentrations Consistent with the sensor of the central location, the outside area shows higher $PM_{2.5}$ and PM_{10} levels on weekdays. This indicates that even areas outside the central urban zones are affected by weekday activities. Early Morning (00:00-5:59) and late night (18:00 - 00:00) are Notably highest on weekdays and weekends possibly due to heating systems. From 6:00-18:00 during the weekdays from 9:00 - 14:59 PM concentrations are lower than rush hours (6:00-8:59) and (15:00-17:59) both periods show increased PM concentrations especially PM_{10} in Figure 19 shows PM_{10} levels on both of time are the same 27.7 µg/m³. On weekends PM concentrations don't have much difference from each other from 33.8 µg/m³,31.2 µg/m³,27 µg/m³ and 24 µg/m³ by effect from the temperature.

Figure 20: PM Concentration on spring outside of the central



$PM_{2.5}$ and PM_{10} Concentrations during the Spring: on the weekdays The graph shows that $PM_{2.5}$ and PM_{10} levels are highest during the rush hour on weekdays because of resident houses, they decreased the use of heating systems. The graph in Figure 20 shows that PM concentrations are higher in the morning - late night on the weekend because the temperature at that time is lower (minimum 13℃). The slightly higher concentrations might be due to additional sources like construction or natural dust that is more active or disturbed during busy human activity.

In conclusion, PM concentration in Gödöllő will increase or decrease by metrology such as wind speed, atmospheric pressure, temperature and heating systems, and transportation. The sensor at the central of Gödöllő has shown that when the sensor changes and the temperature increases residents house are decreased using the heating system and PM concentrations are decreased PM_{10} less than 14.5 µg/m³ and $PM_{2.5}$ less than 12 µg/m³ and PM concentration on weekends are higher than weekdays is opposite way from the end of the winter season. The sensor of the outside of the central Gödöllő PM concentration is higher than the central and similar to each other Even though the change of season will reduce the amount of PM concentration for the weekdays and weekends don't have much difference like the central because it near the highway (3M) and most of the heating system in that area are traditional wood stove.

5. Conclusions and proposals

The research investigated the factors that impact the levels of particulate matter (PM) focusing on $PM_{2.5}$ and PM_{10} in Gödöllő , Hungary. The study aimed to pinpoint the origins of particulate matter in two areas the city center of Gödöllő and outside of the center close to a highway. By utilizing sensor low cost based data collection methods the researchers sought to comprehend how circumstances and human behaviors influence PM levels in these settings and seasons from February to May.

In the city center, its observed that particulate matter levels tend to go down as temperatures go up. This trend is linked to the use of heating systems that run on gas in the downtown area. With rising temperatures the demand, for heating decreases leading to emissions and subsequently reducing particulate matter (PM) levels. Moreover, when comparing the center to the area close to the highway there is less traffic congestion in the city center. This lesser traffic density results in decreased vehicle emissions, which helps concentrations of PM_{10} and $PM_{2.5}$ particles.

In the outside of the center near to the highway the levels of particulate matter (PM) were consistently higher compared to the city area. The presence of the highway meant that traffic from vehicles was a contributor to PM emissions . Specifically diesel-run vehicles release quantities of PM_{10} and $PM_{2.5}$ leading to increased levels of particulate matter (PM). Additionally, the outside of the city center utilizes heating systems including wood-burning stoves, which release high amounts of PM especially during colder seasons A. The combination of traffic and diverse heating methods results in elevated concentrations of particulate matter (PM) in comparison to areas.

Environmental factors also played a role in shaping the levels of PM concentration. Warmer temperatures usually led to decreased levels of Particulate Matter (PM) because of dispersion. Conversely high humidity could cause particles to increase in size and clump together resulting in PM concentrations. Wind speed had a scattering impact as winds typically correlated with PM levels due to increased air circulation and reduced stagnation as highlighted. Additionally atmospheric pressure influenced the levels of Particulate Matter with high pressure systems leading to stable air conditions and less dispersion allowing pollutants to accumulate.

A study comparing the center of Gödöllő and the outside of the center, near the highway showed variations in Particulate matter levels. The city center typically had PM concentrations affected by heating systems and decreased traffic (Zhou et al., 2020).On the hand the rural region displayed levels of Particulate matter attributed to a mix of heating systems and heavy transportation .The study revealed health dangers linked to levels of particulate matter (PM) particularly $PM_{2.5}$ in Gödöllő and its surroundings. Data analysis showed that outside of the center near the highway 75% of the gathered $PM_{2.5}$ samples exceeded the World Health Organization (WHO) guidelines for 24-hour exposure . These results emphasize the health risks associated with prolonged exposure to heightened $PM_{2.5}$ levels.

Exposure to $PM_{2.5}$ may result in issues such as inflammation and decreased lung function. These tiny particles can penetrate into the lungs leading to complications and worsening conditions like asthma and bronchitis . Individuals residing in regions with traffic and heightened exposure to $PM_{2.5}$ are at a risk of facing these breathing difficulties, which can be worsened by other environmental factors. Prolonged exposure, to levels of $PM_{2.5}$ is known to be associated with issues. Research indicates that these tiny particles can enter the bloodstream leading to inflammation throughout the body and raising the chances of heart attacks and strokes . When $PM_{2.5}$ is present in the blood it can harm blood vessels increasing the likelihood of incidents in individuals with existing health conditions.

Certain groups are more susceptible to the effects of being exposed to $PM_{2.5}$. These groups include children, older adults and individuals with existing health problems. In regions with levels of $PM_{2.5}$ these populations face a risk of health complications due to their heightened vulnerability to respiratory and cardiovascular ailments .

To improve air quality in Gödöllő and nearby areas, the following proposals outline key further research techniques, measures, strategies:

i. Analyzing Chemical Components for Identifying Sources Perform chemical studies on PM_{10} and $PM_{2.5}$ samples to better understand their . This will assist in identifying the exact sources of particulate matter, allowing for focused air quality management.
ii. Initiate long-term studies to monitor the health impacts of PM exposure over time. This data will help shape air quality regulations. Also, we should increase the number of

monitoring stations. This will allow for continuous tracking of air quality trends and enable quick identification of pollution hotspots.

iii. Implement strategies to decrease vehicle emissions by promoting the use of cars improving traffic flow efficiency and enforcing stricter vehicle emission regulations. Encourage the adoption of heating systems like heating using natural gas and support the transition to renewable energy sources such as solar power for residential heating and energy requirements. This shift can reduce dependence on wood-burning stoves and fossil fuels resulting in decreased particulate matter emissions.

iv. Create initiatives to educate the community and increase awareness regarding the sources of air pollution and its effects on health. By doing this people may be inspired to embrace habits that help enhance air quality like decreasing reliance, on vehicles and opting for heating options.

v. Improve Regulatory Compliance; Collaborate with national agencies to implement and uphold stringent air quality standards.

vi. Encourage Transportation; Provide benefits for cars and enhanced public transit to lower emissions, from vehicles.

By putting these ideas into action we anticipate an impact on the air quality in Gödöllő to get better and under global standards WHO, a healthier living environment for local residents.

6. Summary

Air pollution, particularly caused by particles, like PM_{10} and $PM_{2.5}$ presents health hazards to the public. This study delves into Gödöllő, a town to Budapest in Hungary to investigate where these particles come from and how they affect health. The goal is to pinpoint the sources of PM10 and PM2.5 measure their levels and grasp the factors that play a role, in shaping these concentrations.

The study was conducted in two distinct locations: the city center of Gödöllő and a rural area near a highway. Data was gathered between February 17th and May 1st 2023 during the shift, from winter to spring. The Honeywell HPMA115S sensor was employed to gauge levels of PM_{10} and $PM_{2.5}$ Other environmental elements like temperature, humidity and air pressure were also documented to explore their connection with particulate matter quantities.

Key findings suggest that PM_{10} and $PM_{2.5}$ concentrations are higher in the rural area likely due to proximity to the highway and traditional wood-based heating. Pearson correlation analysis revealed that temperature and pressure have an inverse relationship with particulate matter levels suggesting that higher temperatures may lead to lower concentrations due to increased atmospheric dispersion. Relative humidity showed a weaker positive correlation with PM concentrations.

The research also examined transportation and heating systems affect the levels of particulate matter. The findings showed that the amount of traffic and residential heating have an impact on the concentrations of PM_{10} and $PM_{2.5}$ in colder seasons when heating systems are used more frequently. Analysis of wind speed revealed that lower wind speeds can lead to increased levels of particulate matter because there is dispersion.

These findings have important implications for public health policies and environmental regulations in Hungary. The results indicate a necessity for approaches to decrease transportation emissions and endorse heating techniques to enhance air quality in Gödöllő. By comprehending the origins and environmental aspects impacting particulate matter levels decision makers can create actions to alleviate air pollution and the health hazards linked to it. Moreover, this research provides valuable insights into particulate matter sources and their impact on public health in Gödöllő, contributing to a better understanding of air quality dynamics and supporting efforts to improve environmental health.

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DECLARATION

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[1] Please underline applicable.