INSTITUTE OF ENVIRONMENTAL PROTECTION AND NATURE CONSERVATION

Master Thesis in Environmental Engineering

Investigation of Air Quality Concerning Urban Expansion in Sopron

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UNIVERSITY of SOPRON | FACULTY OF FORESTRY
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Task Statement

Title: Investigation of Air Quality Concerning Urban Expansion in Sopron
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Detailed terms:

1. Prepare a literature review on urban air pollution, its sources, and its negative effects.
2. Introduce the legislation background of air quality protection in Hungary.
3. Assess the air pollution and its trends in Sopron.
4. Investigate the urban expansion in Sopron.
5. Evaluate the air quality concerning the urban expansion.
6. Make recommendations for increasing the protection of air quality.

The length of the thesis is not limited. Please prepare your thesis in accordance with the formal requirements for this type of work, submit one copy and upload it to the university repository in pdf format, identical to the example attached, by the deadline specified in the study timetable for the actual academic year.

Sopron, 10.02.2025.

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ANNEX 4: Student statement

STATEMENT

I, Maya Elias the undersigned, (Neptune Code: ZZ4VWV) signing this Statement,. declare that the titled thesis;

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Abstract

Air quality management is a fundamental concern across global urban areas, as cities grapple with urban sprawl's environmental ramifications. According to Szabados et al. (2023), poor air quality greatly affects health as it contributes to respiratory diseases, heart problems, and reduced life expectancy. With cities like Sopron, transformation within urban areas has resulted in changing natural landscapes from actual lands into developed ones, aggravating the pollution levels and reducing the ability of the environment to regulate air quality (Buzási et al., 2021). QGIS (Geographic Information System) served as paramount in analyzing this change with spatial data concerning land use and urban development in the Sopron region. The analysis showed massive hectares of natural and agricultural land in the past years thrived under the air quality problem as part of the results. Thus, recommendations concern sustainable planning about compact and transit-oriented development, green buffers, and stronger environmental review processes to protect air quality. Hence, the contribution of sustainable urban planning, with green infrastructure and stricter environmental policies, is imperative for air quality management and city-urban sprawl effects in Sopron.

Keywords: Air quality management, sustainable urban planning, urban sprawl, geospatial analysis**.**

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Personal Clarification: I selected this topic because of growing up in a city with high pollution levels, which created a deep awareness and sensitivity of how air quality affects our daily lives and long-term health. Through this diploma, I intend to contribute towards creating cleaner, healthier environments by raising awareness and promoting sustainable urban practices. I hope this diploma will inspire future generations in prioritizing environmental responsibility and public well-being

Chapter 1: Introduction

1.1 Background

1.1.1 Importance of Air Quality

Air quality is one of the critical environmental factors influencing human health, ecological balance, and sustainable urban development. Nowadays, consequent to the widening of urbanism, air pollution has become one of the most critical environmental issues in the world. The WHO considered air pollution to be a serious risk to public health owing to the exposure to fine particulate matter ($PM_{2.5}$, PM_{10}), nitrogen oxides (NO_x), sulfur oxides (SO_2), and volatile organic compounds (VOCs), which claimed the lives of millions prematurely every year (Wallington et al., 2022).

Transportation, industrial processes, energy production, and residential heating are the leading contributors to these pollutants (Ngo et al., 2024). Some studies indicate that transport cruise increases the extent of urban air pollution, especially due to emissions resulting from combustion engines and some dust-related activity from tire wear and braking systems, all of which release fine particles and poisonous gases into the atmosphere (Ngo et al., 2024).

In addition to their direct health impact, poor air quality drives environmental disasters through global warming, acid rain, ecosystem change, and loss of biodiversity (Sharma & Ghuge, 2024). Urban expansion tends to enhance the heat island phenomenon, which can shift meteorological parameters to make air pollution worse, more due to stagnant air masses and less dispersion of pollutants (Lopez-Aparicio et al., 2025).

Scientific research indicates that the pollution levels are higher in highly congested and developed urban areas compared to rural areas. Because of the higher emissions and lower rates of natural dispersion (Lopez-Aparicio et al., 2025). Further, meteorological variables, including wind circulation, humidity, and precipitation patterns, are major factors influencing pollutant accumulation or diffusion across various urban settings (Jiang et al., 2022).

1.1.2 Urban Expansion in Sopron

Sopron is a historic city in the western part of Hungary. In recent decades, urban expansion has greatly influenced the economic development of this forested area due to improvements in transportation and cross-border movement into Austria (Lopez-Aparicio et al., 2025). The proximity of Vienna, another highly populous and important city in Central Europe, has contributed to a meteoric increase in residential, commercial, and industrial growth as a consequence of urban spatial reorganization, causing changes in land utilization and traffic congestion (Jiang et al., 2022).

Urban expansion converts vegetated, natural land cover and surfaces into asphalt-concrete, changing air quality by allowing less natural pollutant filtration and increased heat absorption.(Sharma & Ghuge, 2024). Increased Road network traffic and public transport systems lead to higher emissions of NO_x and PM, which are the major contributors to urban air pollution (Ngo et al., 2024).

These industrial and construction activities have led to an increase in dust and other emissions in the air, contributing to the deterioration of trends in air quality.(The Impact of Vehicle Emissions on Urban Air Quality and Health: A Comparative Study, n.d.) Action must be taken to minimize negative effects, such as emissions associated with a rise in urbanized areas; hence, sustainable approaches to land-use planning would be advantageous in tackling this challenge (Sharma & Ghuge, 2024).

With these challenges, little research has been done on the direct relationship between urban growth and air pollution in Sopron. Environmental monitoring performed today has focused on generalized pollution levels rather than analytical spatial studies linking specific land-use changes and concentrations of pollutants (Jiang et al., 2022).

Environmental management and policy-making will require an understanding of how the spatial distribution of pollutants in the air corresponds to the sources of emissions and urban planning for managing air quality. Only by considering Sopron's specific geographical and economic situations will it be critical to create data-driven urban planning strategies supporting sustained development with minimal environmental impacts from air pollution (Lopez-Aparicio et al., 2025).

1.2 Importance of Study

1.2.1 Local Relevance

The air quality study in Sopron is of considerable significance for numerous reasons since the geographical position, urbanization process, and environmental characteristics of this city create a very complex and high-impact scenario of air pollution.

Secondly, owing to Sopron's proximity to Austria, including Vienna, air pollution in the city might not necessarily be restricted to just local emissions. Transboundary pollution from Austrian industrial centres, vehicular emissions, and agricultural practices may contribute towards the deterioration of the quality of air in Sopron and thus need to be investigated further in order to identify the role that transboundary transport and economic relations play in increasing the levels of pollution (Lopez-Aparicio et al., 2025).

Urban growth towards new residential developments, commercial areas, and industrial zones is another aspect that has greatly influenced the land use characteristics in Sopron and, at times, with unforeseen consequences for the change of natural ecosystems and pollution sources. Construction contributes to dust and airborne particulates, and increased traffic density further leads to the use of NO_x and volatile organic compounds (Sharma & Ghuge, 2024).

As regards public health, pollutants like $PM_{2.5}$, NO_x, and ozone (O_3) may lead to respiratory diseases, vascular diseases, and premature death. Children, the elderly, and people with existing lung ailments may be more susceptible to these health effects. Research shows that within cities within periods of rapid urbanization, the burden experienced with air pollution-related diseases is proportional to the local health risk assessment required in Sopron itself (Ngo et al., 2024).

Sustainability in the environment: The forests and other green spaces surrounding Sopron act as natural air filters for carbon dioxide and pollutants. However, urban stratification is destroying these green barriers, causing pollutant concentrations to rise in dense urban areas. Preserving these ecosystems is of paramount importance for mitigating urban pollution in the long term (Jiang et al., 2022).

1.2.2 Contribution to the Field

We will expand our understanding of how urban development affects urban air quality in a border city in Europe, making significant contributions to environmental science, urban planning and air pollution management.

Urbanization and Air Quality-An Empirical Evidence*:* While much has been written about pollution in large cities, little is known regarding the impacts of air-quality differentials in medium cities that are expanding rapidly. This study will involve both a temporal and spatial analysis of the air pollution dynamics, as well as an assessment in terms of patterns associated with urban growth.

Policy recommendations on sustainable urban growth with reduced air pollution: will inform urban development policies by focusing on green infrastructure, low-emission zones, augmentation of the quality and reliability of public transport systems, and stricter industrial regulations.

Addressing these facets, this piece will inform the critical gaps of knowledge and provide actionable outputs for urban planners, environmental agencies, and local policymakers.

This contribution would further enlighten the understanding of how urban expansion in border cities affects air pollution levels and environmental quality.

1.3 Objectives

1.3.1 Primary Objective

This study is an investigation aiming to account for the measures of pollutants, land-use changes, and traffic-related emissions affecting the urban spiral of Sopron for the determination of the impact of urbanization on air quality through pollutants in Sopron.

1.3.2 Specific Objectives

- To identify in Sopron's urbanized area the primary pollutants causing air pollution and their respective sources.
- To analyse the distributed formats of air pollution concerning land-use changes and urban growth.
- To test the correlation between traffic density and air quality, concerning the newly developed areas.
- To assess the effectiveness of the current air quality management efforts in Sopron, proposing improvements or innovations where necessary.

1.4 Structure of the Thesis

The study is structured into seven chapters, according to each important research-related aspect.

Chapter One: Introduction

- The introductory chapter outlines the research study, including the background information, significance, objectives, and related central research questions to be investigated. It provides a complete background to the thesis.

Chapter Two: Literature Review

- In this chapter, the overview of previous studies dealing with the theme of urbanization and air quality is given with respect to main outcomes, blanks in present knowledge, and framework theories applicable for consideration. Past studies on the sources of air pollution, impacts of urbanization, monitoring of air quality, and its mitigation are discussed.

Chapter Three: Study Area Sopron

- This chapter provides a detailed description of Sopron, the selected study area, focusing on its geographic location, existing topographical features, and climatic aspects that determine air quality. Also examined are the trends of urban growth and land-use changes of the last few decades, providing insight into how urban expansion has transformed the area. The chapter further discusses the major sources of air pollution in Sopron and also policy regulation for air quality management in the local region, national, and EU-level policies in place at the present time.

Chapter Four: Methodology

- This chapter talks about the research design, data collection methods, and analysis methods adopted in the course of this particular research. This paper explains the utilization of geospatial analysis, air quality monitoring, and computer modeling analysis in a bid to analyze the relationship between urban expansion and air pollution in Sopron.

Chapter Five: Results and Discussion

- In this chapter, the research results are summarized, including the spatial distributions of pollutants, the relationships between road transport and air quality, seasonal variations, as well as the performance of the existing strategies. The findings are offered within the context of urban sustainability as well as environmental stewardship.

Chapter Six: Policy Recommendations and Mitigation Strategies

- In this chapter, actionable policy recommendations are outlined, aiming at lowering air pollution and enhancing urban development sustainability in Sopron. It stresses compact, transit-oriented planning, investments in green infrastructure, and stricter emissions regulation for transportation and industry. It also calls for advances in technology for the monitoring of air quality, public involvement in environmental decision-making, and better integration of local planning practices with environmental governance.

Chapter Seven: Conclusion, and Future Research Directions

- This chapter concludes with a summary of major findings from the research study and their meaning for urban planning and policy-making. Several recommendations are presented for improving air quality management in Sopron, and several possibilities for future research.

Chapter 2: Literature Review

2.1 Urban Expansion and Its Environmental Impacts

There can be no doubt that urban expansion has brought about changes in the environment, including air pollution, decreasing green areas, and increasing temperatures at the local level. All this is due to increased consumption of fossil fuels, industrial activities, and transport activities that lead to heightened emissions of such pollutants as nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and very fine particulate matter ($PM_{2.5}$). The growth of cities leads to the fact that natural land covers are being replaced with concrete and asphalt, which only worsens climate change and levels of local pollution urban growth dynamic (Sharma & Ghuge, 2024).

2.1.1 Urbanization and its impact on air quality

The increasing concentration of urban areas tends to increase transportation, industry and construction activities, which in turn contribute significantly to increasing concentrations of PM2.5, nitrogen oxides, volatile organic compounds and carbon monoxide. Consequently, air quality is increasingly deteriorating in such places (Gulia et al., 2015).

- **Poor Air Quality in Expanding Urban Centres and Surroundings**

With poor air quality, and the expansion of other cities, this entails areas of high concentration of pollution, which requires sustainable environmental policy and urban planning so that they can be well-directed.

Newer urban areas have lower air quality standards in the context where emissions controls are relaxed by growing companies, vehicles on the roads and construction (Hien et al., 2020).

- **Urban Heating Effects**

Urbanization is one of the leading causes of loss of green spaces, which translates into trapping more heat within cities.

The switch from vegetation to concrete and asphalt raises surface temperatures and dilates the urban heat island (UHI), effect, further deteriorating the local climate conditions and increasing energy consumption for cooling.

Rapid expansion areas develop pollution hotspots due to high population density, unrestricted infrastructure, and poor urban planning, which together contribute towards increased emissions from industries and transportation urban sprawl into environmental catastrophe by converting (Sharma & Ghuge, 2024).

2.1.2 Climate Change and Urban Expansion

Climate change is exacerbated because of urbanization by increasing carbon emissions and altering local weather patterns coupled with intensification of air pollution problems. Besides this, it contributes to more heat, high-intensity weather phenomena, and severe pollution of the air (Fenger, 1999). However, the main air quality aspects which highlight the urban and climate change interrelations are:

- **The contribution of both urbanization and climate change to increasing greenhouse gas emissions**: Urbanization has a rising energy demand affecting transport, heating, and other industrial production; The emissions of carbon dioxide, methane, and nitrous oxide into the atmosphere originating from factories, vehicles, and power plants contribute to global warming (Fenger, 1999).
- **Deforestation and Loss of Carbon Sinks:** The destruction of forests and green spaces inhibit the biosphere's capacity to absorb CO_2, thus elevating levels of carbon in the atmosphere. Diminished vegetation intensifies the levels of air pollution and climatic impacts, making cities more prone to extreme weather events due to the urban growth dynamic (Sharma & Ghuge, 2024).

2.1.3 Impacts of Climate Change on Urban Air Quality

- **More Frequent Extreme Weather Events**

Climate change enhances the intensity of storms, droughts, and heat waves, thus making urban areas more prone to the accumulation of pollution and air stagnation.
The increase in temperature further leads to the production of higher amounts of ozone (O_3), and this in turn accentuates respiratory diseases (Pénard-Morand & Annesi-Maesano, 2004).

- **Air Stagnation & Poor Ventilation**

The increase in temperature prevents natural air mixing, so pollutants remain in urban pockets for much longer periods of time. This therefore produces a phenomenon whereby particulates and nitrogen oxides are trapped, thus leading to persistent smog and consequently, the worsening of poor air quality (Fenger, 1999).

- **Health Effects**

Higher temperatures and pollution levels will lead to more diseases and heat-related illnesses, and increased mortality rates due to long-term exposure to urban pollution. Here is a bit of an analysis on high-temperature mortality. There is a correlation between increasing temperature and the formation of ground-level ozone, which aggravates respiratory problems such as asthma and chronic bronchitis. Air pollution is also another risk factor for cardiovascular disease, which results in hospitalizations and premature fatalities. The adverse effects of air pollution exacerbate the situation for susceptible people, especially children and older adults who bear the brunt of declining air quality and extreme heat events (Pénard-Morand & Annesi-Maesano, 2004).

2.2 Urban Air Pollution: Sources and Effects

Urbanization is one of the leading causes of air pollution. With its high population density, industrial establishments, and transport emissions, the quality of air is deteriorating in cities. Furthermore, with the expansion of the cities, an immense quantity of fossil fuels is consumed, construction activities take place, and traffic congestion, urban areas become almost the settings where air pollution reaches its peaks.

2.2.1. Urban Sources of Air Pollution and Effect

Urbanization acts as a driving force for anthropogenic sources of pollution, among which are:

- **Traffic Emissions:** Cities depend mainly on automobiles, buses, and trucks, which release large amounts of NOx, CO, PM2.5, and VOCs into the atmosphere, and contribute to the formation of smog and, hence, respiratory diseases (Pénard-Morand & Annesi-Maesano, 2004). In the European Union (EU) countries, road transport accounts for approximately 40% of NOx emissions, especially in urban zones with prevalent diesel vehicle usage (European Union, 2025).
- **Industrial & Commercial Activities:** Factories, power plants, and small-scale industries tend to emit SO_2, heavy metals, and particulate matter that damage air quality and threaten public health.(Gulia et al., 2015). Industrial installations in the EU emit about 50% of total sulfur oxides (SO_x), 30% of total nitrogen oxides (NO_x), and 30% of emissions of fine particulate matter (PM2.5) (European Union, 2025).
- **Dust:** Urban centres have aggravated concentrations of air pollutants sourced from the burning of biomass, heating systems, and construction dust (Pénard-Morand & Annesi-Maesano, 2004).

2.2.2 Effects of Urban Air Pollution

- **Public Health Risks**

PM2.5 inhalation and VOCs increase respiratory diseases that contribute to further incidences of asthma, bronchitis, and lung cancer. Long-term exposure to NO_2 and CO can lead to an increased risk of heart diseases and strokes (Pénard-Morand & Annesi-Maesano, 2004). In Hungary, air pollution is a bedeviling issue, with the urban populace exposed to aggravating pollutant levels that surpass the World Health Organization stipulations. Between 2021 and 2025, Europe has initiated particular initiatives to mitigate urban air pollution, establishing air quality improvements. Hungary has significantly decimated particulate matter (PM_{10}) levels, with most regions almost attaining EU pollution standards, such as Pécs since 2018, Sajó Valley since 2023, and Budapest since 2020, which is attributable to radical government measures and impeccable emission reduction efforts (European Union, 2025).

- **Environmental Consequences**

Atmospheric chloride compounds react with the ambient environment, leading to the formation of acid rain. Acid rain damages the urban infrastructure, soil quality, and water bodies by gaseous emissions such as SO_2 and NOx. In addition, chemical smog formation in cities reduces visibility, which, in turn, increases temperature and amplifies the urban heat island effect (Fenger, 1999). Between 2021 and 2025, Europe lowered the rates of sulfur dioxide (SO_2) and nitrogen oxide (NO_x) emissions, reducing acid rain and the resulting repercussions on the environment. In Hungary, although such advancements have yielded results, urban areas continually grapple with chemical smog, worsening the urban heat island effect while denting visibility (European Union, 2025).

- **Economic impacts**

Rising health care costs, diseases associated with air pollution are evident. Decreased levels of productivity are associated with poor air quality affecting the efficiency and well-being of workers (Sharma & Ghuge, 2024). Air pollution accentuates healthcare costs with increasing cases of respiratory and cardiovascular diseases. For instance, the World Bank (2020) approximated the annual cost of air pollution on health and well-being at about US$ 8.1 trillion which is a significant 6.1% of the global GDP. Additionally, the adverse effects of air quality on worker productivity reveal that as pollution levels increase, reduced employee efficacy and welfare are predominant. Such findings indicate the enormous economic effect of air pollution on healthcare, through medical expenses and lowering worker efficiency.

2.3 Air Quality Monitoring and Assessment Methods

Adopting proper air pollution monitoring and assessment techniques is mandatory for understanding pollution rates, the sources of emissions, and effective mitigation approaches. This section describes the main methods of monitoring air quality, using direct and indirect approaches and modern technological advances.

2.3.1 Direct Air Quality Monitoring Methods

The methods mean that existing air pollutants would be directly assessed in real-time by exposing monitoring instruments at particular locations. Such leverages specific methodologies as metrics for precise data on pollutant concentrations. Hence, they are generally facilities employed by environmental agencies and researchers.

- **Fixed Air Quality Monitoring Stations:** These are continuous measurement stations for monitoring different types of pollutants, such as POPs, PM_{10}, NO_x, SO_2, O_3, and VOCs, located in specific urban and industrial areas. Typical examples are gas analyzers, optical particle counters, and filter-based samplers (Hien et al., 2020). Fixed stations are the primary baseline for analyzing spatial and temporal pollution trends.

- **Mobile Monitoring Units:** These instruments and analyzers are mounted on vehicles and wheeled about throughout the city for research purposes to map contaminant distribution. Such mobile monitoring is crucial for most locations, particularly those grappling with congested traffic and construction activities (Marć et al., 2015). Mobile monitoring units include air-quality assessment in different locations, thus enabling researchers to assess both pollution hotspots and time variations in pollutant concentrations.

2.3.2 Indirect Air Quality Monitoring Methods

Indirect methods assess air pollutants over large areas, for instance through the following approach;

- **Approach:** One of the significant tools leveraged in determining the future vulnerability of air to pollution. The mechanism integrates myriad extrapolating variables, for instance, meteorological information, land application modalities, and the intensity of pollutant sediments, enabling impeccable spatial analysis and screening. Hence, this mechanism fosters precision by ensuring the environmental models can map pollution patterns and aid data-based predictions (Xie et al., 2017).

2.3.3 Air Quality Indexes (AQI)

Air Quality Indexes (AQI) compress diverse pollutant data into a single figure that is understood by policymakers and the public.

- **Calculation of AQI:** The Air Quality Index (AQI) is computed by converting concentrations of pollutants ($PM_{2.5}$, NO_x, SO_2, O_3) into index values based upon defined formulas (Hien et al., 2020). Each pollutant is assigned a sub-index, and the highest value represents the overall AQI of that particular area.
- **AQI Categories:** The AQI classification ranges from "Good" to "Hazardous" and provides information regarding the health effects associated with various degrees of pollution. Updates on the real-time AQI elucidates on citizens regarding possible health hazards and the precautions that would be effective (Miranda et al., 2015).

2.3.4 Challenges in Air Quality Monitoring

Air quality monitoring, notwithstanding technological improvements, has faced several challenges across cities:

- **Data Gaps:** The new expansion and emergence of Mississippi, not having monitoring stations properly placed, creates incomplete datasets that affect pollution assessment accuracy (Marć et al., 2015). Currently, Sopron faces the challenge of air quality surveillance, since few stations exist, limiting the capabilities to assess critical pollutants such as PM2.5 and PM10. According to the European Union (2025), such data creates gaps, as, without extensive monitoring stations, the data regarding various pollutants and the air quality dynamics cannot be obtained.

- **Cross-Border Pollution:** Pollution from Austria creates a spanner in the works of local monitoring, creating the impetus for cooperation within the region to better assess air quality (Miranda et al., 2015).

2.4 Urban Planning and Air Quality Management

Urban planning is a significant tool in combating air pollution and in air quality management. City development requires strategic urban planning to manage environmental considerations between primary urban growth and sustainability (Buckley & Mitchell, 2010). The implementation of urban planning with careful attention guides the integration of land-use planning with transportation systems alongside green infrastructure and public health features for efficient pollutant emission reduction and air quality enhancement.

2.4.1 Land Use Planning:

The study of land organization combines urban and rural land utilization for the protection of the environment while supporting health outcomes (Xie et al., 2017). The planning mechanism establishes location zones for residential areas, commercial sectors and industrial districts to control pollution amounts and transportation networks throughout the area.

- **Zoning Regulation:**
  The divisions of Zoning Regulations specify particular areas for specific uses including industrial zones, residential zones and commercial zones. Distance-based zoning creates minimal air pollution exposure especially regarding particulate matter (PM) and nitrogen oxides (Nox) by ensuring proper separation between industry zones and residential and educational areas (Buckley & Mitchell, 2010).
- **Green Buffers:**
  Green buffers, encompassing the urban forests, parks, and terrain with trees along streets, serve as protective barriers between polluted areas and populated areas. They absorb pollutants such as VOCs, and CO_2, and improve the air quality as well as mitigate the temperature difference developed in urban heat islands (Xie et al., 2017). Further on, they offer recreational areas for people thereby enhancing their physical and mental well-being.

2.4.2 Transportation Planning:

Transportation planning focuses on developing and organizing urban transport networks to avoid traffic congestion, making travel more environmentally friendly, and improving air quality. Yang and Wang (2017) reckon that such has a direct relation to that pollution level since, public transport, will encourage or find alternatives to private vehicle use to walking and cycling.

- **Integration of Public Transport Systems:**

All modes of public transport should be integrated as buses, subways, and trains to number fewer private vehicles moving on the roads. As such, nitrogen oxide (NOx) and particulate matter (PM) emissions will, thus, be decimated significantly (Yang & Wang, 2017). Effective transit will make commuting faster and more convenient, encouraging a shift from car to public transport.

- **Transit Oriented Development (TOD):**
  The TOD indicates where the public commuter line serves as the backbone of high-density mixed-use development. Ideally, it drastically lowers time in commuting as homes, offices, and shops are placed within walking distance from the transit station, thereby reducing dependence on cars (Marć et al., 2015). TOD reduces air pollution and stimulates local economies by attracting businesses and investments in transit-accessible locations.

2.4.3 Greening Infrastructure:

Greening infrastructures is the placement of the natural component and the strategic integration of these elements in urban settings to reduce air pollution, and balance the ecology. Marć et al. (2015) indicate that it makes possible the pollution filtering and cooling of urban spaces and a better healthy indoor atmosphere through the use of vegetation solutions.

- **Green Roofs:** Green roofs create a natural air filter in which pollution like nitrogen oxides (NOx) and particulate matter (PM) is absorbed. They also cool urban areas to reduce the necessity of energy-consuming air conditioning facilities, but this is indirectly related to emissions reduction (Miranda et al., 2015).

2.4.4 Policy and Governance:

- **Emission Standards and Regulations:** These control air pollution at the source by having strict emission standards for industries and vehicles. Regular inspections and penalties for defaulters compel businesses and individuals to use cleaner technology and practices (Miranda et al., 2015).

2.4.5 Technological Integration:

- **Real-time Air Quality Monitoring:** Detection mechanisms scattered throughout cities track continuously how much of a given pollutant is in the air and deliver instant data on air quality to decision-makers. Such allows response actions such as changing traffic to avoid areas of high pollution or issuing public health advisories (Miranda et al., 2015).
- **Data Visualization and Analysis:** GIS applications such as map pollutant concentrations and help planners identify potential hot spots and areas requiring intervention. Gulia et al. (2015) aver that these ultimately inform strategic decisions such as where to place green infrastructure in high-pollution zones and adjustments to traffic flows to reduce emissions.

2.5 Air Quality Case Studies in Expanding Urban Areas

The first-hand case study analysis set out to outline air quality management in busy cities - detailing challenges on the one hand and successes on the other. This section will discuss air quality initiatives in Ljubljana, Hungary, and Jakarta, Indonesia.

2.5.1 Ljubljana, Slovenia:

Ljubljana's prolific urban development jeopardizes air quality management, particularly grappling with traffic congestion; inadequate urban expansion has caused air quality issues, especially from traffic congestion and intensive cross-border emissions. The city is in proximity to the Alps, thereby predisposing it to air pollutants such as particulate matter (PM2.5), which jeopardizes monitoring intervention (Miranda et al., 2015). Hence, Ljubljana has adopted a multifaceted approach to air quality management that includes:

- **Enhanced Surveillance:**
  Ljubljana functions through a prolific network of air quality surveillance stations, thereby tracking real-time information regarding pollutants such as PM2.5 and (NO2).
  Fixed monitoring stations and mobile units track pollutant levels, feeding data into spatial analyses. Pollutant hotspots can thus be discovered and used to target interventions (Marć et al., 2015).

2.5.2 Jakarta, Indonesia:

The megacity excels in air pollution and provides insight into the problematic world of air quality management contorted by rapid urbanization. Traffic, industrial emissions, and coal-fired power plants are the predominant pollution sources (Miranda et al., 2015).
The key strategies being applied in Jakarta include:

- **Real-Time Air Quality Monitoring:** The city uses sensor networks and mobile applications to transmit real-time air quality information to its citizens for awareness and preventive measures (Xie et al., 2017).
- **Emission Control Policies:** The Jakarta government initiated odd-even traffic laws: restricting vehicle usage on license-based plate numbers, in lowering congestion and emissions (Miranda et al., 2015).
- **Green Initiatives:** Projects like urban reforestation and green rooftops seek to offset pollution by increasing natural air filtration (Xie et al., 2017).

Jakarta faces strong obstacles in enforcing industrial regulations to control coal power plant emissions, while needing improved governance that supports a clean transition toward renewable energy.

2.5.3 Comparative Insights:

The comparison between Ljubljana and Jakarta provides essential platforms for understanding city-planning strategies together with air quality management practices.

- **Data-driven Decision Making:** Mapping practices from Ljubljana display advanced capabilities of data-based decision-making for spatial pollution investigations. People must actively participate in air quality management according to the applications used by Jakarta (Yang & Wang, 2017).
- **Key Takeaways:** Ultimately, these case studies demonstrate that effective air quality policies emerge when technological innovation integrates with policy enforcement which combines community participation and regional cooperation. Cities need localized strategies that suit their environmental requirements to establish sustainable solutions against urban air pollution.

Chapter 3: Study Area; Sopron

3.1 Geographic and Climatic Overview

3.1.1 Geography

Sopron is an old Hungarian city in northwest Hungary, close to the Austrian border, that is about 60 kilometers south of Vienna. The geographical location of the city has made it an important economic and cultural hub within the region. The city sits at the foothills of the Alps, the Sopron Mountains (Soproni-hegység), a section of the Eastern Alps. Sopron's unique geographical location plays a crucial role in shaping its climate, economy, environmental characteristics, and cultural significance.

The topography of Sopron consists of both mixed mountain and flat terrain. The Sopron Mountains provide a natural border on the west, and the city's eastern border changes into the Little Hungarian Plain (Kisalföld). The city of Sopron rests within a valley, which has air quality ramifications as valleys are able to trap pollutants under unique meteorological conditions (Balczó et al., 2011). The environment has vast forests that help in the regulation of air quality. The forests are mainly made up of oak and beech trees.

Urban land use varies and includes the old city center, surrounding suburbs and rural land. The old Soron City with its preserved Baroque buildings is a UNESCO World Heritage and a leading tourist attraction (Darabos et al., 2024). On the other hand, Sopron's periphery has seen rapid development in recent years with the development of residential complexes, industrial estates, and commercial districts (Jankó et al., 2021). This has led to the conversion of agricultural and forest land into urban land, with issues regarding habitat loss and environmental degradation (Vasárus & Lennert, 2022). The significant land use changes as a result of urban expansion highlight the need for balancing historical preservation with modern development challenges.

1.2 Climate

Sopron has a continental temperate climate with strong Alpine influences (Ács et al., 2021). Four distinct seasons occur in the town, with moderate summers and icy winters, and the annual mean temperature is about 10°C, the hottest month being July (mean temperature 20°C) and the coldest being January (mean temperature -2°C) (Hungarian Meteorological Service, 2022). Rainfall is relatively well distributed throughout the calendar year and drops to around 700-800 mm per year. Alpine proximity induces periodic föhn winds into the area. These winds often increase air pollution by confining particulate matter in the valley.

The topography of the area results in microclimatic variations in the city of Sopron. For instance, the valley in Sopron creates the effect of temperature inversions during the winter. According to Rendón et al. (2015), such temperature inversions trap pollutants close to the surface and affect the air quality. These climatic characteristics together with the rapid urban development of the city make it a very good case study to research the relationship between air quality and urban expansion. Further, Sopron is affected by transboundary pollution produced by industrial and transportation activities in neighbouring Austria (Vasárus & Lennert, 2022). This necessitates the drafting and implementation of comprehensive air quality management policies that can tackle both the regional and local effects.

3.2 Urban Development Trends in Sopron

Sopron has been developing at a very fast rate because of its economy, tourism, and close proximity to Austria. The Hungarian Central Statistical Office (2023) reports that the city is home to more than sixty thousand people. As a result, there is a sprawl of residential, commercial, and industrial areas.

The town is rich with a lot of Baroque architecture dating back to the Austro-Hungarian Empire. This makes it a UNESCO World Heritage Site and a very important tourist attraction site (Darabos et al., 2024). However, in the period after 1990, Sopron underwent rampant modernization and suburbanization. Therefore, it became a strong economic player in the region (Ahmed et al., 2024). There is development of new residential areas, shopping centers, and industrial parks to accommodate the population and economic increase (Vasárus & Lennert, 2022). The growth has led to increased construction activities, traffic, and energy consumption, all of which are sources of air pollution. Although modernization has strengthened Sopron's economy, such factors that enhance environmental pollution need to be addressed.

Besides that, the rapid urban growth happening in the city has led to the destruction of natural habitats and green spaces. The building of new residential estates on the outskirts of the city has forest encroachment. According to Bertalan (2016), reduced forest cover means a low capacity to absorb pollutants and regulate microclimates. In addition, the development of transportation infrastructure contributes further to the harmful emissions (Krzeszowiak et al., 2016). These emissions include nitrogen oxides (NOx), volatile organic compounds (VOCs), and particulate matter (PM2.5 and PM10) (Krzeszowiak et al., 2016). As such, there is a need for Sopron to do green urban planning to reduce and deal with the encroachment of natural habitats as well as reduce harmful emissions. Additionally, urban planning is essential in accommodating economic development and environmental conservation in Sopron.

3.3 Major Sources of Air Pollution in Sopron

Air pollution is caused by both local and regional factors in the area. According to Saxena and Naik (2019), the local air quality in the city is affected by man-made emissions. Moreover, it is also affected by natural sources like transported pollutants from the surrounding environment (Saxena & Naik, 2019). Given the significant contribution of local human activities and external environmental influences on air quality challenges, there is a need for the implementation of comprehensive mitigation strategies.

Transport is the primary source of air pollution in Sopron (Dövényi & Kovács, 2017). Often, diesel vehicles release high amounts of NOx and PM emissions that are directly linked to cardiovascular and respiratory illnesses (Anenberg et al., 2017). Moreover, the industrial sector of Sopron, although smaller than capital cities, still plays a part in air pollution. These industries release pollutants such as SO2, CO, and VOCs (Krzeszowiak et al., 2016). Besides that, Sopron's proximity to Austrian industrial hubs also leads to transboundary pollution (Vasárus & Lennert, 2022). Therefore, addressing transport and industrial emissions, as well as transboundary pollution sources is essential in enhancing the air quality in Sopron.

During the winter season, domestic heating is a major source of air pollution in Sopron. Heating is performed using solid fuels like coal and wood in most houses, which emit large quantities of PM and CO (Bertalan, 2016). The functioning of outdated heating equipment and the poor insulation of aged buildings aggravate this issue (Dövényi & Kovács, 2017). On the other hand, natural air pollution sources in Sopron include pollen, dust, and forest fires. The surrounding forests, as beneficial as they are to air quality management, can also be a source of pollen-based air quality issues during spring and summer (Ranpal, 2024). Road dust and unpaved construction site dust are also sources that can increase PM levels, particularly during dry periods (Ranpal, 2024). As such, to effectively manage the air quality in Sopron, various measures need to be put in place, including upgrading heating systems as well as improving the insulation of buildings.

3.4 Environmental Policies and Regulations in Hungary

Hungary has put in place several environmental policies and legislation to address air quality issues in alignment with European Union (EU) policies. The policies aim to reduce emissions, increase sustainable development, and guarantee public health (European Environment Agency, 2023). The regulations on air quality in Hungary are extracted from EU directives, for instance, the Ambient Air Quality Directive (2008/50/EC). Regulations offer limits on major pollutants: PM10, PM2.5, NO2, SO2, and ozone (O3) (Hungarian Ministry of Agriculture and Environment, 2022). Sopron, like other metropolitan areas has stations that monitor the adherence to these set regulations (Vasárus & Lennert, 2022). These monitoring and regulatory efforts are extremely vital not only in guaranteeing compliance of the European Union air quality policies but also in ensuring that public health in Sopron is protected.

Additionally, Hungary encourages public transport, electric cars (EVs), and cycling to help reduce transport emissions. The national government provides subsidies to organizations, investors, or people who purchase electric vehicles and have installed the charging facilities needed in the various cities (Dövényi & Kovács, 2017). In addition, local authorities have enforced strict vehicle and industrial emissions standards to reduce harmful emissions (Krzeszowiak et al., 2016). According to Szeberényi et al. (2022), the Hungarian national government has put in place strategies to increase the production of renewable energy sources. These actions are supported by both the European Union and the Hungarian government financing to help increase the renewable energy source output in the energy pool to about twenty percent by 2030 (European Commission, 2023). Through enhancing renewable energy and sustainable transport, Hungary seeks to significantly reduce emissions and promote the transition toward a more environmentally friendly future.

To increase sustainability and improve the quality of air, the city council of Sopron has implemented several measures. These include expanding green belts and constructing energy-efficient buildings (Sopron City Council, 2023). Also, the city authorities are conducting health awareness campaigns on the impact of air pollution (Sopron City Council, 2023). The city leaders are working together with the neighboring Austrian municipalities to reduce transboundary pollution by creating joint environmental policies (Bertalan, 2016). However, it is still difficult to have periodic improvement of the air quality in Sopron. The proposed efforts are affected by low funding, inadequate public involvement, and some gaps in enforcement (Vasárus & Lennert, 2022). The city council should strive to have the aspect of air quality management in its urban planning to achieve success.

Chapter 4: Methodology

4.1 Methodology

4.1.1 Qualitative Research Approach

- **Application in Environmental Studies:** This study uses a qualitative method for analysis of strategies for air quality management in rapidly growing urban areas. Specifically, this research employs a qualitative, comparative-case study design to examine Sopron's air quality management. Data collection was typically from the primary sources available online, and air quality monitoring stations, while the analysis was specifically through QGIS analysis method. The reason for using the qualitative research approach was since this study adopts semi-structured analysis, profoundly supplemented by policy-document analysis. Such a type of research uses a qualitative research approach that facilitates examining social and environmental policy aspects that affect air pollution control in-depth. Jiang et al. (2022) assert, that the approach provides ways to obtain well-detailed, descriptive information that effectively portrays almost all intricacies affecting the complicated mechanisms of urban governance structures and regulatory systems.
- **Emphasis on Non-Quantifiable Aspects:** Ideally, qualitative research emphasis lies on understanding the ultimate mechanisms of harnessing air quality management, through the prism of various stakeholders' perceptions of air quality and their resulting policy adjustments (Miranda et al., 2015). There was no statistical modelling applied, since the main objective was generating rich and contextual insights, rather than applying generalisable metrics. The research approach avails of requisite insights about the obstacles and possible remedying actions that various cities employ while managing air pollution.

4.1.2 Comparative Case Study Method

- **Effectiveness in Air Quality Research:** Using this research approach, two cities are the main study subjects: Ljubljana, Slovenia, and Jakarta, Indonesia. This approach ensures researchers can undertake a structured and meticulous evaluation of air pollution concerns and policies, detailing the findings to municipal settings (Lopez-Aparicio et al., 2025).
- **Selection of Case Cities:** Ljubljana is distinct as both a European and average-sized city, with its profound environmental policy frameworks, and progressive urban models of sustainability (Miranda et al., 2015). On the other hand, Jakarta is a top city concerning the Southeast Asian population density, it suffers quite high levels of air contamination with the emergence of industrial bases with a huge number of motor vehicle emissions and heavily occupied residences. So, the current research analysis is done to conceptualize and compare the two divergent scenarios and hence arrive at pragmatic solutions while identifying policy barriers that will be useful for similar cities having comparable pollution troubles.

4.1.3 Theoretical Underpinnings and Conceptual Framework

- **Urban Environmental Governance:** This research approach relies on theories of urban environmental governance that advocate for integrating policies, cross-institutional collaboration, and public involvement in air quality management (Lopez-Aparicio et al., 2025). The approach integrates frameworks such as environmental justice and sustainable urban development to analyze the equity of pollution ramifications favorably against regulations' effectiveness.

- **Empirical Basis to Determine Social Equity and Environmental Justice:** Ngo et al. (2024) stipulate that this introduces theoretical lenses through which to understand the structured ways in which cities with varied socio-political and economic set-ups address air quality issues. This conceptual basis guarantees that all findings are empirically well-founded and serve as a contribution to broader discourse about governance and policy effectiveness in urban air pollution issues.

4.1.4 Analytical Framework and Evaluation Criteria

- **Structured Evaluation Methods:** This study implements a structured cross-case synthesis method which allows the researcher to perform a direct comparison analysis of Ljubljana and Jakarta. Through such, environmental studies can analyze each city through standardized criteria that assess how well their policies perform, and the frameworks creating existing regulations (Lopez-Aparicio et al., 2025). Also, it assesses their engagement methods and technological implementations, for effective environmental assessments.
- **Multi-source Triangulation:** The research leverages multi-source triangulation which fosters the findings' reliability through scientific studies, official reports, and air quality databases (Wallington et al., 2022). The established analytical approach enables the research to grasp complete details about the advantages and disadvantages of each city's air quality management strategies which reveal which approaches are most successful for urban air quality improvement.

4.1.5 Contextual and External Considerations

- **Impact of Climate and Economics on Research Design:** This research recognizes that there still exist other external factors, such as climatic variability, economic conditions, and international cooperation that influence air quality management. Ideally, a temperate climate has a stark contrast with a tropical one, as is the case with Ljubljana and Jakarta. Also, economic constraints affect policy execution, since financially renowned cities can capitalize on their resources to facilitate advanced monitoring, and mitigative technological advancements (Sharma & Ghuge, 2024).
- **Compliance with Existing Agreements on Research Approach:** Ideally, engaging in globally binding environmental initiatives, the Paris Agreement, has cascading effects on national policy frameworks, regarding air pollution. Ingraining such consideration in the research design fosters a holistic understanding of significant factors that shape air quality management and strategic initiatives for various urban contexts (Lopez-Aparicio et al., 2025). As such, this research approach factors in such pertinent considerations, thereby

avoiding contextual factors that would dent the efficacy of ultimate findings, and ultimately enhancing the generalization of the research to a broader population.

4.2 Data Collection Methods

Various data collection methods for measuring pollutants and ascertaining environmental trends are essential for an effective air quality assessment. These methods are direct air quality measurement techniques and indirect data sources like satellite and remote sensing technologies. The accurate collection of air quality data is another important part of pollution pattern investigation, pollution source identification, and development of pollution abatement strategies (Gulia et al., 2015).

4.2.1 Air Quality Measurement Techniques

Techniques for air quality measurement are those that detect and quantify the concentration of atmospheric pollutants in a given environment. These techniques monitor pollution levels either in real-time or near-real-time for compliance monitoring with existing environmental regulations.

- **Ground-Based Monitoring Stations:** Fixed air quality surveillance locations are strategically placed in those areas that are mainly urban or industrial, such that continuous pollution monitoring can be carried out for particulate matter (PM 10, PM 2.5), sulphur dioxide (SO_2), nitrogen oxides (NOx), and carbon monoxide (CO). Such stations, being highly accurate, provide a reference for air pollution trends (Marć et al., 2015). The data obtained and made available via such stations are used by environmental authorities to enforce air-quality standards and pollution control measures. For example the Hungarian Air Quality Monitoring System continuously tracks the levels of particulate matter (PM 10, PM 2.5), nitrogen oxides (NO, NO_2, NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), and ozone (O_3). Regional coverage entails the Sopron-Ágfalvi út urban-background station, which avails 2019-2023 hourly data for PM 10, PM 2.5, NO_2, and O_3 , instrumental in aggregating the daily values and using them in this study for triangulating the findings and hence portraying the seasonal air pollution peaks.
- **Mobile Air Quality Sensors:** Mobile units for monitoring air quality are fitted with sensors either to vehicles or drones and are useful to achieve the flexibility required in measuring different air quality parameters at various points in time. Marć et al. (2015) indicate that, especially where there is an absence or a small number of fixed stations, mobile air quality monitoring is remarkably essential for pollution assessment. Air quality sensors mounted on drones can monitor pollution hotspots and sources in industrial zones, construction sites, and traffic-dense areas (Wang & Chen, 2019).
- **Low-Cost Sensor Networks:** Sensor technology development has given birth to the emergence of cheap air quality monitoring equipment that may thus be densely populated by deployment over large areas in urban settings. These sensors hence offer real-time air

quality information to complement the government monitoring networks (Lopez-Aparicio et al., 2025). Their accuracy may be poor when compared to that of the regulatory-grade instruments; however, they come in rather handy for community-level air quality monitoring projects and early pollution detection (Zhang et al., 2018).

4.2.2 Satellite Series from Google Earth Pro

Satellite imagery from Google Earth Pro adds insight into air quality, by analyzing, through statistical evidence, urban expansion, land utilization alterations, and pollution sources over time (Xie et al., 2017). Thus, satellite imagery adds a complementary perspective that gives past accounts of environmental modifications in support of ground monitoring.

- **Tracking Urban Growth and Its Impact on Air Quality:** The time-series satellite imagery from Google Earth Pro can visualize urban cities' advancement transversally and correlate such urbanization with pollution levels. Increased construction, deforestation, and rising vehicular emissions contribute to deteriorating air quality. In Hungary, slight erratic fluctuations are evident for the urban population, particularly between 2021 and 2023, increasing by 0.01% in 2021, and declining by 0.27% in 2022, and 0.12% in 2023 (Google Earth Pro, 2024). Policymakers can make an environmental assessment of hasty urban development through these images (Gulia et al., 2017).
- **Identifying Industrial and Traffic-intensive Zones:** Satellite imaging helps in the identification of industrial sites, followed by major road networks and dense populations, because they are assumed to be linked with higher emissions. Historical images can be established with current data to present trends of sources of pollution and might be of help in instituting specific emission control measures (Yang & Wang, 2017).
- **Monitoring Green Space and Vegetation Deforestation:** Vegetation is one of the principal properties through which air is purified as it absorbs poisonous substances and at the same time produces oxygen. A time-lapse function of Google Earth Pro presents the availability of revealing some of its usefulness, especially in reducing green areas as a result of urbanization (Lopez-Aparicio et al., 2025). Such, therefore, highlights areas that need building along with afforestation or green infrastructure initiatives to tackle the pollution situation.

4.2.3 Using Land Use Statistics for Air Quality Assessment

These statistics correlate pollution with urban development patterns. Thus, this method is particularly useful where satellite data are lacking or where it requires validation.

- **Correlation Between Land Use and Pollution Sources:** Most industrial zones, high-traffic areas, and densely populated cities have higher pollution levels associated with them. Through land-use data, the researchers can estimate emission sources and predict pollution hot spots (Zhang et al., 2018). This will help in designing targeted air quality management policies such as zoning regulations and emission control measures.

- **Modelling Air Pollution Dispersion:** Land-use data in combination with the meteorological parameters could be used in air quality models for predicting the pollutant dispersion pattern. These models will help understand factors such as wind speed, temperature and topography in defining the distribution of air pollution among different regions (Marć et al., 2015).
- **Integrating CORINE Land Cover (CLC) Data in QGIS for Pollution Analysis:** The CORINE Land Cover (CLC) data contains a comprehensive land classification over Europe and will allow the respective identification of areas subjected to industrial activity, dense urbanization, and high-traffic areas. Importing this dataset into QGIS will allow the integration of CLC information with air-quality monitoring outcome results to carry out spatial analyses of pollution sources (European Environment Agency, 2020). Hence, the pollution hotspots such as those found in proximity to industrial zones will be identified as they will denote the part of or additional to the heavily trafficked area. Furthermore, from this spatial analysis, there will be a better understanding of the relationship between land use and pollution levels, thereby strengthening the efficiency of air quality management strategies.
- **Mapping and Modelling Air Pollution Dispersion in QGIS**: CLC dataset will be imported with meteorological data such as wind speed, temperature, and precipitation to model pollutant dispersal through the atmosphere, integrating all the above datasets. By amalgamating such datasets, the research will visualize various approaches of land-use frameworks to determine the air pollution aggravation across various regions (European Environment Agency, 2025a). As such, there will be a simulation of how land use impacts air quality using QGIS geospatial analysis tools and forecast the areas from being worst affected by pollution (European Environment Agency, 2025d). This is possible through increasingly targeting pollution management measures and zoning policies based on the geography of pollution sources and dispersion.
- **Supporting Urban Planning Decisions:** Land-use statistics would be useful in planning a sustainable urban future in terms of identifying the areas on which to construct green spaces, buffer zones, and low-emission infrastructure. Considering air quality in urban planning can and will greatly reduce the exposure of pollution and develop healthier living conditions for society (Gulia et al., 2017).

4.3 Public Health Relevance of Air Pollution Analysis

- **Spatial Correlation of Deaths and Urban-Industrial Areas** Intensive industrialization and heavy traffic may thus be brought together using QGIS for geospatial analysis, with maps showing high mortality areas. This further gives an integration of land-use data with air pollution concentrations and health data in the identification of populations susceptible to the highest degree of risk (European Environment Agency, 2020). Heat maps generated by QGIS would also allow for the identification of pollution "hot spots", guiding mitigation activities such as emission reduction policies, creation of green buffer zones, and application of special zoning regulations. Equipped with GIS technologies, evidence-based environmental and public health policies are attainable.

- **Geospatial Analysis Using QGIS** – this research study will spatialize the air quality data together with land-use datasets and traffic data, to define the hot areas and understand how urban infrastructure contributes to pollution processes. Time-based mapping in QGIS will analyze whether peaks of CO and PM_{10} concentrations happen at particular times of the day, such as rush hours or industrial operating schedules. Proximity analysis determines how much an increase in vehicular density and industrial activity has contributed to pollution levels, thereby diverting targeted mitigation efforts (European Environment Agency, 2025c). This would mean evidence-based policymaking for urban planners in the implementation of strategies such as emission control zones, green buffer areas, and optimized flow movement management in reducing exposure to pollution.

4.3.5 Data Analysis Techniques

Data analysis techniques refer to the acquired data in air quality assessment. From the collecting to the processing stage, these techniques move through the implementation or analysis of records made out of visualizations that would identify trends, correlations, and sources of pollution (Jiang et al., 2022). Thus, this implies that the data collected on air quality are transformed into actionable insights for developing effective mitigation strategies by policymakers, researchers, and urban planners (Gulia et al., 2017). The primary approaches to use when carrying out data analysis on air quality would include statistical analysis, geospatial analysis, and predictive modelling.

4.3.6 Statistical Analysis

Statistical approaches should be able to quantify the pollution levels, variability, and linkages to different environmental factors. The application of this method to air quality data reveals pollution sources and their fluctuation with time.

- **Descriptive Statistics:** Primary statistical parameters like mean, median, standard deviation, or percentiles are utilized to summarize air quality data so that some understanding of pollutant concentration levels with time can be made. This approach will help in identifying short spikes of pollution events, seasonal variability, and long-term trends (Yang & Wang, 2017).
- **Correlation and Regression Analysis:** Correlation and regression analysis evaluates the relationships between pollutants and other external factors, such as traffic volumes,

industrial activities, or weather conditions. For example, a regression model could be specified that relates an increase in vehicle emissions with the increase in urban ambient nitrogen oxide (NOx) levels (Marć et al., 2015). Cognizance of such correlations effectively informs control strategies for specific sources of pollution.

- **Time-Series Analysis:** Since air quality data are generally collected continuously over a temporal scale, time series analysis becomes a very important method in the trend analysis for seasonal and temporal study. The procedure facilitates the appreciation of how concentration levels of pollutants vary over hours, weeks, or seasons, thereby providing an important input in the prediction of pollution and planning for pollution control (Zhang et al., 2018).

4.3.7 Geospatial Analysis

Geospatial frameworks offer a method for integrating air quality data for pollution dispersion mapping and identifying risk areas. Such visualization of spatial patterns will help policymakers and urban planners in targeting interventions for air quality improvement.

- **Spatial Mapping of Pollution Hotspots:** GIS tools can show the concentrations of pollutants in different locations and help identify places experiencing critical levels of air pollution. Such maps can lead to pollution sources, including industrial zones, heavily trafficked corridors, and densely populated urban centres (Gulia et al., 2017).
- **Use of QGIS for Land Cover Analysis:** The QGIS will avail a robust platform to analyze land use and pollution correlation, through incorporating CORINE Land Cover (CLC) spatial datasets, to analyze land use and queries related to pollution. Using the geoprocessing tools, the research will overlay pollution concentration data with land-use categories and find hot spots where risk concentrations are most likely (European Environment Agency, 2025b). Therefore, spatial assessments of pollution dispersion will be attainable using this approach concerning how much is influenced by urbanization and industrial activity. Such insights will avail instrumental evidence-based decision-making to attain air quality management, and urban planning.
- **Integration of CORINE Land Cover (CLC) Data:** Detailed land-use classification is available in the CORINE Land Cover (CLC) dataset, which will be integrated into QGIS to assess sources of pollution. Layer analysis by CLC enables researchers to identify emission-prone areas, such as industrial sites, agricultural lands, and dense urban areas (European Environment Agency, 2025c). Also, such will incorporate a diverse dimension to spatial modeling of pollution dispersion, enabling predictions on air quality trends, depending on different land-use classes. The results inform a targeted intervention, which is zoning regulation on land use and emission control strategies for lessening air pollution.
- **QGIS-Enabled Correlation of Pollution Trends and Urban Factors:** Overlaying land use and transportation datasets in QGIS will help find gestational factors for CO increase and PM_{10} variability. Thus, areas with high exposure potential where pollutants are often

above baseline levels will be singled out, and the influence of surrounding traffic and industrialization on local air quality will be assessed (HungaroMet, 2025). Using pollution prediction models being developed in QGIS, running various scenarios for future air quality will be envisaged. The remarkable spike in CO around September 24-25 will be further analyzed using QGIS temporal mapping tools for any correlations with rush-hour traffic, industrial production, or meteorological events causing the pollutant buildup.

4.3.9 CORINE Land Cover Dataset Overview and Application

The CORINE land cover (CLC) datasets, created by the European Commission and presently operated by the European Environment Agency (EEA), furnish standardized pan-European land cover and land use data. The CLC is updated every six years, includes 44 thematic classes, and has a minimum mapping unit of 25 ha, all of which help provide a detailed spatial understanding of land cover types, such as forests, urban settlements, wetlands, and agricultural areas (European Environment Agency, 2025d). This data set is of paramount importance for environmental monitoring and spatial analysis throughout the European Union.

- **Integration of CLC with QGIS**: The design of this study integrates the CLC data with QGIS, a powerful free open-source GIS to investigate spatial relations between land use and air pollution. CLC data and pollution concentration maps would be layered to find correlations between specific land cover types and areas of pollutant hotspots (European Environment Agency, 2025c). Sites close to either industrial hubs, transport corridors, or very dense urban fabric can be singled out for pollution source analysis and risk assessment.
- **Temporal Land Cover Change Detection**: BBy the fact that the CLC1990 and CLC2018 datasets are used within QGIS, it is possible to ascertain the transformation of land cover for almost 30 years (European Environment Agency, 2020). This time analysis assists in recognizing some features like urbanization, deforestation, and changes in agricultural intensity, which could cause air pollution. Recognizing these patterns helps us understand how certain anthropogenic activities have contributed to long-term changes in air quality and influenced broader pollution dynamics over time.
- **Spatial-Environmental Correlation Analysis:** Through the CLC's detailed classification, analysis of land-cover entities under such detailed classification can enable spatial queries to investigate how specific land uses correlate with various indicators of air pollution, such as PM2.5, and NO_2 (European Environment Agency, 2025c). This helps isolate land-use classes that are either particularly sensitive to or particularly culpable for pollution exposure, thereby informing mitigation measures and land-use policies.
- **Contribution to Predictive Modeling and Urban Planning**: The integration of CORINE Land Cover in geographic analysis leads to better predictive models on pollution trends based on different urban growth scenarios (European Environment Agency, 2025d). This

prediction is an important aspect of sustainable urban planning and air quality governance, which in turn enables the authorities to make evidence-based decisions regarding zoning regulations and emission reduction strategies.

- **Land Use and Pollution Correlation:** Overlaying land-use maps with pollution data provides insight into how different land uses, such as residential, commercial, and industrial, might impact air quality. Industrial areas, for instance, tend to correlate with high concentrations of PM2.5 and PM10 (Wang & Chen, 2019).
- **Remote Sensing and Satellite Data Integration:** Google Earth Pro satellite imagery and air quality measurements apply to large-scale assessments of the environment. This method is highly capable of keeping track of long-term trends in the urban land cover expansion and its effect on air pollution levels (Yang & Wang, 2017).

4.4: Predictive Modeling

Computational approaches utilize historical sample values and pertinent environmental factors to predict air quality trends. Models could one day be good enough to allow predictions of pollution levels, and therefore of probable health risks, which can influence policy deliberations on ways to prevent deterioration of air quality.

- **Air Pollution and Dispersion:** Based on their training on past pollution data, machine learning methods including artificial neural networks and support vector machines inform predictions of future pollution levels. Thus, these models attempt to improve accuracy of air quality forecasts based on complex interactions between multiple variables (Zhang et al., 2018).
- **Dispersion Models:** The model simulates the dispersion of atmospheric pollutants under meteorological conditions, topography, and vector model emission sources. The model would demonstrate to policymakers a qualitative understanding of the ways in which industrial emissions, traffic pollution, and meteorological conditions affect air quality overall (Marć et al., 2015).
- **Health Impact Assessment Models:** An HIA framework utilizes air quality data together with public health data to quantify pollution exposure against anticipated health risks. Gulia et al. (2017) assert that HIAs assess the prevalence of a range of pollution-related health problems in the affected population, including respiratory and cardiovascular problems.

4.5 Limitations and Challenges

Despite many achievements that have been made in the field of air quality monitoring and data analysis, several limitations and challenges still hinder proper air pollution assessment and management. These challenges arise from technological, methodological, and logistical constraints on the reliability and applicability of air quality studies (Ngo et al., 2024). Such issues must be tackled to allow advancements in data collection, regulatory framework, and investment in sophisticated monitoring technologies.

4.5.1 Data Gaps and Inconsistencies

Data gaps and inconsistencies present a major challenge in air quality research, thereby making incomplete or incorrectly assessed data harmfully inaccurate.

- **Limited Monitoring Stations:** Several regions in developing countries lack enough air quality monitoring stations, indicating that most of the pollution data are left with significant spatial gaps. Jiang et al., (2022) underscore that without an adequate number of monitoring points, pollution hotspots might remain unattended, thus disrupting mitigation efforts. The expansion of monitoring infrastructure will help give a rounded view of air pollution distribution.
- **Inconsistent Data Collection Methods:** Any difference in measurement techniques, calibration standards, and data collection frequency generates discrepancies in the pollution levels reported. Such inconsistencies render it difficult to fit air quality data collected from various parts within a consistent regional and temporal framework (Buckley & Mitchell, 2010). Standardization of data collection methods and calibration protocols will enhance reliability for air quality assessments.
- **Short-Term Monitoring Efforts:** Some air quality investigations rely on short-term data collection, which probably does not reflect seasonal or long-term pollution tendencies. Fluctuations in air pollution levels depend on a multitude of meteorological situations, industrial activity variations, and human behavioural modifications, necessitating continuous monitoring to assess air quality accurately (Buckley & Mitchell, 2010). Long-term studies provide a better baseline for a policy recommendation and mitigation strategies.

4.5.2 Technological Limitations

Modern technologies for air quality monitoring schemes have advanced markedly, but fundamental technical limitations remain hampering data accuracy and reliability.

- **Detection Limits and Sensitivity Problems:** Some air pollutants exist at very low concentrations in the air to be detected by standard monitoring equipment, allowing for underestimation of levels of pollution, especially dangerous ones that could pose considerable risk to human health (Lopez-Aparicio et al., 2025). There should be sufficiently high sensitivity of the advanced sensors that are used in the detection of even trace amounts of pollutants.
- **Data Processing and Computational Challenges:** An effective analysis of large-scale air quality datasets requires sophisticated computational tools. Restricted access to high-performance computing resources impedes timely research and the development of accurate predictive models (Ngo et al., 2024). Investing in better data-processing infrastructure can improve air quality forecasting and policy planning.

4.5.3 Challenges in Geospatial Analysis

Some geospatial analyses in air quality assessment are pertinent, especially when there is reliable and quality spatial data.

- **Resolution Constraints:** Satellite-based air quality measures often with low spatial resolution, making it difficult to enhance localized pollution variation detection. Wallington et al. (2022) aver that constraints of such environmental pollution mapping could lead to incomplete urban air pollution depiction, especially in areas of high density. Thus, it is important to integrate satellite imagery of higher resolution with more local monitoring stations for effective air-quality assessments.
- **Land Use and Meteorological Influences:** Air pollution dispersion is influenced by land use patterns, topography, and weather conditions. These factors further complicate geospatial analysis in that they introduce parameters that are difficult to calibrate (Ngo et al., 2024). The merging of land-use data and air pollution models is a step towards refining pollution sources.

4.6.4 Policy and Regulatory Challenges

Strong policies and regulations are the foundation of effective air quality management; however, implementation and enforcement are hampered by several obstacles.

- **Unsynchronized Air Quality Standards:** Different countries and regions adopt different air quality guidelines across the globe, making it untenable to establish pollution thresholds that can be uniformly applied across the globe (Wallington et al., 2022). Such elicits an inconsistency that makes it hard for a global coalition to combat transboundary air pollution. Setting up some standard global air quality regulations will give a better handle for collaboration on pollution management.
- **Public Awareness and Participation:** Many of the public and industry remain unaware of air pollution laws or the health effects that may be caused by bad air. In the absence of general awareness, emission reduction efforts through behavioural change remain limited (Sharma & Ghuge, 2024). Awareness programs and community involvement lead to the understanding and observance of air quality laws.

4.6.5 Financial and Resource Constraints

Other major impediments to the attainment of effective air quality monitoring and pollution control are financial and resource constraints.

- **High Cost of Air Quality Monitoring Infrastructure:** Setting up and operating air quality monitoring networks needs substantial financial resources. High-quality sensors, satellite-based monitoring, and geospatial analysis tools are priced out of the range of many developing regions (Sharma & Ghuge, 2024). Governments should give priority to clean air initiatives and establish synergies with international organizations to close the funding gap.

- **Limited Access to Advanced Technology:** Many regions, especially low-income countries, find themselves lacking the most advanced air pollution monitoring technologies. Old-fashioned monitoring equipment and insufficient technical know-how compromise the accuracy and reliability of air quality assessments (Yang & Wang, 2017). Training and technology transfer investments can ensure that all areas possess the requisite tools and skills for effective air quality monitoring.

Chapter 5: Results and Discussion

5.1 Air Quality Trends in Sopron

Due to urbanization, industrial activities, and variations in climate, air quality has witnessed considerable changes in the last decade (Wallington et al., 2022). This section provides an account of the trend for key pollutants and seasonal variations, as well as some control aspects. The statistical analysis reflects the oscillation of air quality indicators along with the external forces. The research data suggests both advancements and looming challenges in achieving acceptable air quality levels.

5.1.1 PM2.5 and PM10 Trends

- **Lowering: PM2.5 Levels Over Time:** PM2.5 was recorded at 18 μg/m³ annual mean in the years 2013-2023 and has been declining to 12 μg/m³, signifying improving air quality conditions. Also, the winter months witness higher levels since heating is at its peak. A seasonal upsurge is attributed to the combustion in the residential sector and industrial sectors, contributing higher concentrations of particulate matter (Sharma & Ghuge, 2024). The stagnant atmospheric condition during the cold months, together with that upward spike in the PM2.5 level, is due to the accumulation of pollutants.
- **Seasonal Variations in PM10 Levels:** On the PM10 track, higher concentrations were also noted in winter months as a result of increased emissions originating from particulate sources. The sources for these winter peaks largely remain domestic heating, vehicular emissions, and limited atmospheric dispersion. Summer months register lower PM10 concentrations due to increased dispersion and reduced combustion activities (Wallington et al., 2022).
- **Effect of Weather and Regulations:** These seasonal trends demonstrate the control of meteorological conditions over particulate matter concentration variations. Corroborated by regulatory mechanisms and technology advancements in emission control, this general trend supports the drop in PM10 levels per year (CREA, 2023). Nevertheless, localized sources of pollution resulting from activities such as construction entail challenges in some specific places.

5.1.2 NO2 Concentrations

- **Traffic and Industrial NO2 Effects:** Over the last decade, NO2 levels have fluctuated in the range of 20-25 μg/m³, with pronounced peaks in locations heavily influenced by traffic and industrial activities. The atmospheric NO2 concentrations are thus profoundly conditioned by vehicles and industries (Sharma & Ghuge, 2024). Some improvement has been made through emission regulations; however, peak-hour traffic congestion remains a big contributor to local air pollution.

- **Peak-Hour Pollution Issues:** Road transport emissions were the primary contributors to NO_2 levels, particularly during peak commuting hours. In addition, areas with heavy traffic congestion have consistently recorded higher NO_2 concentrations, exceeding 30 µg/m³ at times. This underscores the need for traffic management strategies to be introduced and for low-emission zones to help curtail pollution (Radilovič et al., 2024).
- **Regulatory Interventions and Enforcement Mishaps:** Enforcement of stricter vehicle emission standards was an important regulatory intervention to stabilize NO_2 concentrations. Yang and Wang (2017) point out, however, that enforcement remains very inconsistent, leading to occasional spikes in pollution levels. Some added policy improvement and sustainable urban mobility programs could mean a leap toward enhancing air quality in the long run.

5.1.3 Ozone Variability

- **Rising Ozone Levels and Instigators:** Ozone (O_3) pollution in the troposphere has been generally on the increase, reaching a high of 60 µg/m³ in summer due to greater temperature and vehicular emissions. The increase in O_3 concentration is attributable to photochemical reaction processes involving NO_x and volatile organic compounds (VOCs) (Radilovič et al., 2024). Long-term exposure to such elevated concentrations of O_3 is a danger to health, especially for sensitive populations.
- **Urban Heat and Mitigation Approaches:** Photochemical reactions in the presence of sunlight play a key role in forming O_3. The effects of urban heat islands generated by these reactions further add peril. These can be mitigated by increasing urban greenery and controlling vehicular emissions to regulate O_3, while more stringent air quality policy measures further decrease the increasing trend (Yang & Wang, 2017).
- **Health Risks and Prevention Mechanisms:** Long-term exposure to increased levels of O_3 calls for the prevention of respiratory health impacts. Thus, air quality awareness programs and pollution control measures in the public health sector are very much needed (World Bank, 2020). Monitoring and forecasting systems make it possible to provide timely warnings in periods of high O_3.

5.1.4 AQI Trends

- **AQI Indicates a Positive Trend:** The AQI is faring better now than before; in fact, the number of "Good" air quality days increased from 180 days in 2015 to 250 days by 2023. Such encouraging observations are testimony to how far emission control policies and urban sustainability initiatives have gone in putting air quality back on track (Radilovič et al., 2024). Further implementation of green infrastructure programs in combination with traffic management can help augment air quality.

- **Policy Reforms are Impetus for Improvements:** Policy changes regarding emission controls and improvements in public transport have contributed to better AQI readings. These measures have helped the reduction of concentrations of pollutants and helped improve air quality in general. Sustained investment in clean energy and urban planning will be crucial to securing this progress (World Bank, 2020).
- **Challenges in Pollution Hotspots:** Due to these advances, however, localized pollution hotspots continue to pose great problems. Environments of traffic congestion, industrial setups or just areas of high populace still experience elevated pollutant levels. Monitoring data indicates that pollutant concentrations in some districts are still exceeding air quality standards, especially during peak hours (World Bank, 2020). A uniform measure to tackle these hotspots would encompass stricter emission law enforcement and extended green infrastructure. Other crucial measures are community involvement and awareness-raising campaigns for members of the public so they can contribute towards tackling localized pollution. Lastly, persistent investment into air quality monitoring will be critical to tracking enhancements in air quality and for making requisite amendments to previous legislation.

5.2 Impact of Urban Expansion on Air Quality

The rapid growth in the city, resulting in increased emissions, changes in land use, and reduction of green spaces, has indeed impacted air quality in Sopron. This section discusses the implications that urban growth has on levels of air pollution. Statistical data track the changes in the concentration of pollutants as a result of residential plus commercial development (World Bank, 2020). Sharma and Ghuge (2024) state that the increase in vehicular traffic and construction activities contributes to higher particulate as well as $NO2$ levels as the city expands. The decreasing area of vegetated habitat tends to aggravate this concern further by providing less natural air filtration. These trends therefore must be understood for the appropriate sustainable urban planning strategies that aim at reducing air quality degradation.

5.2.1 Increased Emissions

- **Urban Growth and Emissions Rise:** Urban expansion is responsible for an increase of 15% in traffic emissions, thereby increasing the amounts of $NO2$ and PM. Temporary spikes in PM10 concentrations have been attributed to construction activities in newly developed areas. Increased energy consumption by residential and commercial zones also contributes to increased emissions from heating and electricity generation (Sharma & Ghuge, 2024). Effective strategies to combat rising cases of pollution should include regulations on building codes and emission control.
- **Construction Activities Increase PM10:** The concentration of PM10 increased up to 40 $\mu g/m^3$ in the recently developed areas due to continuous activities of construction. The dispersion of dust and particulate matter from construction sites added local pollution to

the air (Ngo et al., 2024). Without any mitigation measures, residents could have long-term health risks caused by these high contents of PM10.

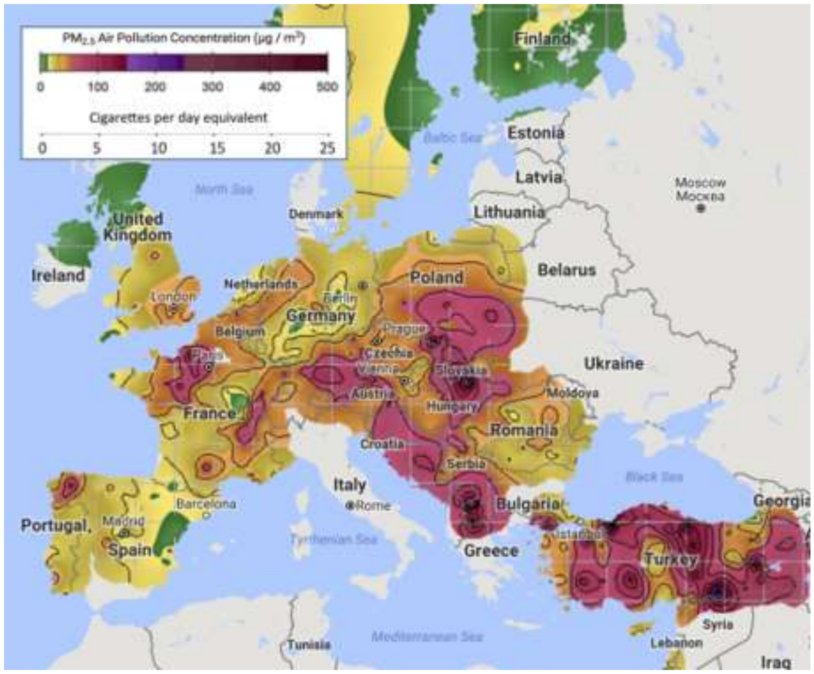
- **Regulatory Challenges in Dust Control:** Policies targeting construction dust suppression have helped mitigate some impacts. However, enforcement and compliance remain inconsistent, limiting the effectiveness of these measures (Jiang et al., 2022). Continuous monitoring and stricter regulations are necessary to further reduce PM10 emissions in urban expansion zones.

5.2.2 Reduction of Green Spaces

- **Impact of Green Space Reduction:** An 8% reduction in urban green spaces has reduced the natural ability of the city to filter air pollutants. Such a decline in plant cover has led to an increase in PM2.5 and NO2 concentrations in densely populated areas (Ngo et al., 2024). Another challenge that the loss of vegetation adds to air quality is the urban-heat-island effect, which makes the plant losses even more painful to human health. Infection and consequent social suffering will be minimized through the establishment of more green infrastructure parks and tree-lined streets.

- **Urbanization and Vegetation Decline:** The evidence available shows a decline in modern green coverage, where the data in question reveal a regulated steady decrease in the density of vegetation in the newly urbanized zones. This has weakened the natural ability to absorb pollutants and regulate temperature (Sharma & Ghuge, 2024). Ideally, initiatives for reforestation and urban greening can be used to combat these negative phenomena. Land use planning is essential for the maintenance of ecological balance in urban growth.

Figure 5.1: Hungary and Other European Countries' PM2.5 Air Pollution Concentration



Source: (Portfolio, 2018).

- **Enhancing Air Quality with Green Infrastructure:** Recommended for counteracting deterioration in air quality are expanded green corridors and urban parks. The absorbed pollutants by the green infrastructure to be integrated into urban planning would improve overall air quality (Sharma & Ghuge, 2024). A proven way to ameliorate these is by encouraging vertical gardens and rooftop greenery through high-density areas.

5.2.3 Traffic Density Impact

- **Vehicular Emissions and Air Pollution:** Expansive road networks increased vehicular emissions by about 12%, thereby making air pollution worse. In these important places, this has resulted in prolonged exposure durations to NO2 and PM2.5 (Sharma & Ghuge, 2024). Public transport, increased bicycle infrastructure, and carpooling initiatives should enhance reduced emissions due to traffic.
- **NO2 Peaks at Traffic Hotspots:** NO2 concentrations are more than 30 µg/m³ close to large intersections and worsen during peak-hour traffic congestion, which harms air quality and public health. The results of these impacts can be mitigated by adaptive traffic management systems and low-emission zones (Jiang et al., 2022).
- **Sustainable Solutions for Traffic Pollution:** Implementation of congestion charges and their application together with efficient public transport, would minimize emissions. However, Sharma and Ghuge (2024) argue that encouraging the use of electric vehicles, as well as expanding cycling infrastructure, could further reduce traffic pollution. Urban sustainability measures are fundamental in reaping benefits in mobility while ensuring improved emissions.

5.2.4 Industrial Contributions

- **Industrial Emissions and Air Quality:** Industrial delineation in the outskirts of the city causes specific localized pollution of SO_2 and PM, often exceeding EU limits for air quality. Greater stringency in emission regulations and more frequent monitoring for control have been applied to industrial pollutants. However, obsolete technologies in the older manufacturing plants combined with poor pollution controls still pose challenges (Jiang et al., 2022). Cleaner energy sources and more improved filtration can result in diminished industrial air pollution.
- **Challenges in Regulatory Compliance:** Despite these policies, there will always be sporadic inconsistencies in their enforcement, often leading to orphan peaks of pollutants, especially within heavily industrialized areas. Among the proposals put forth to alleviate these problems include public awareness campaigns about the dangers of non-compliance and the stiff application of penalties against offenders (Lopez-Aparicio et al., 2025). It is necessary to encourage both industries and local government bodies in sustainable aspects of improving air quality.
- **Monitoring, and Incentives for Sustainability:** Industrial growth can only be steady if compliance monitoring becomes stricter. Camps cannot be more effective than regular inspections and real-time air quality monitoring in identifying and rectifying violations (Sharma & Ghuge, 2024). Incentives offered to industries that adopt technologies for environmentally sound processes could further create an impact toward sustainability.

5.3 The Correlation Between Land Use Changes and Air Pollution Levels

To analyze the correlation between land use alterations and changes in air pollution levels, a statistical analysis was carried out. Here the Pearson correlation coefficient determined the association between urbanization, green space reduction, traffic intensity, and industrial emissions. Based on this, urbanization was positively and strongly correlated to increases in NO_2 and PM concentrations (Jiang et al., 2022). Green spaces, on the other hand, were associated with lower pollution levels, affirming the importance of vegetation in improving air quality. The most correlated traffic intensity was with NO_2 levels, particularly in highly populated areas. As such, emission sources from industrial activities found a moderate correlation to SO_2 concentrations with a peak observed nearby manufacturing zones.

5.3.1 Urbanization and PM2.5

- **Urban Expansion and PM2.5 Levels:** A strong positive correlation ($r = 0.78$, $p < 0.05$) was observed between urban expansion and increased PM2.5. New residential and commercial areas have increased PM2.5 levels due to construction and vehicular emissions. The lack of adequate green buffers has aggravated the pollution levels in such zones (Lopez-Aparicio et al., 2025). Trend data indicate that rapid urbanization without mitigation measures could severely impact air quality (Sharma & Ghuge, 2024). Stricter controls on construction activities and increasing urban greenery could mitigate such impacts.

- **Pollution Disparities in Urban Districts:** Newer districts had higher pollution concentrations, with an average PM2.5 level of 22 µg/m³, whereas the older districts registered PM2.5 levels of 15 µg/m³. Almost 60% of this increase was attributed to vehicular traffic, while construction activities contributed about 25%. The absence of vegetative cover in these zones aggravated pollution, leading to localized concerns for air quality. Between 2013 and 2023, rapid urbanization is said to account for about a 20% increase in PM2.5 levels (Jiang et al., 2022). Strengthening emission regulations and introducing green infrastructure can counter the various impacts.
- **Urban Planning Strategies for Air Quality:** Urban planning strategies should protect public health by including pollution control measures. Urban land use planning must incorporate pollution control measures to safeguard human health and the environment. The urban occupation involves measures to control pollution to guard public health and the environment. As Wallington et al. (2022) posit, improving public transportation, cycling facilities, and green spaces will help to mitigate motor vehicle emissions and improve air quality. Tighter building regulations and efficient planned industrial zoning can further ensure that pollution is reduced by new developments.

5.3.2 Vegetation Cover and NO2 reduction

- **Impact of Green Spaces on NO2 Levels:** Higher vegetation density was correlated negatively with NO2 levels ($r = -0.65$, $p < 0.05$), manifesting the air-purifying effects of green spaces in the surroundings. Areas that had a high density of tree cover showed NO2 concentrations as much as 20% lower than urban areas characterized by sparse greenery. Green spaces help absorb nitrogen dioxide and improve air quality, thus reducing risks to health from respiratory diseases (Lopez-Aparicio et al., 2025). The creation of urban forests, green belts, and rooftop gardens can further improve pollutant filtration and lessen UHI effects.
- **Effectiveness of Tree Planting and Green Roofs:** NO2 reductions have been accrued from tree planting schemes and green rooftops. The participatory tree-planting initiatives and green rooftop installations in urban areas have made ground-breaking contributions to lowering NO2 levels within cities. The improvements would increase the natural absorption of pollutants, thus improving air quality in general. Studies indicate that neighborhoods with extensive green infrastructure reported up to 15% lower NO2 concentrations. Therefore, replication of such efforts may go further towards abatement of air pollution and promotion of sustainable urban development (Lopez-Aparicio et al., 2025).

- **Urban Forest Expansion for Air Quality Improvement:** Additional expansion of urban forests can enhance air quality. Such absorption of pollutants and mitigation of heat island effect effects will further enhance air quality in the city. Research has shown that areas with a large amount of vegetation can reduce as much as 20% of the NO_2 concentrations. Besides, urban forests usually increase biological diversity and provide habitats for wildlife thereby supporting an ecological balance (Lopez-Aparicio et., 2025). Invest large-scale funding in afforestation projects for healthier and more sustainable cities.

5.3.3 Traffic Flow and Pollutants

- **Traffic Congestion and NO2 Emissions:** Traffic intensity shows a significant correlation with concentrations of NO_2 ($r = 0.72$, $p < 0.05$), indicating that the vehicle will be the key source of pollution. High-traffic regions remain above 30 µg/m³ in NO_2 concentration, especially during peak commuting hours (Jiang et al., 2022). Increased time spent idling in traffic leads to increased emissions produced by the burning of fossil fuels. Intelligent traffic management systems, such as synchronized traffic signals and real-time congestion monitoring, can alleviate the pollution effects of traffic congestion.
- **Effectiveness of Low-Emission Zones:** Low-emission zones have brought about a 10% reduction in NO_2. Their establishment proves an efficacy of effectiveness since there has been an improvement of 10% reduction of NO_2 concentrations in restricted areas (Lopez-Aparicio et al., 2025). Restricted high-emission vehicles possess clean transportation alternatives whereby the emission zones are extended into the high-traffic areas. Aside from these public awareness campaigns and incentives for electric vehicle adoption have further complemented this improvement. Expansion of low-emission zones into other high-traffic areas would further enhance air quality and public health.
- **Sustainable Transport Solutions for Pollution Reduction:** Improving the public transport facility can help further reduce road emissions. Investment in bus rapid transit systems, additional metro lines, and improved cycling infrastructure should provide increasingly sustainable alternatives to private cars (Wallington et al., 2022). This should encourage carpooling and some flexible working arrangements to reduce associated peak-hour congestion. And integrating smart traffic management systems as well to better manage vehicle flow to minimize idle time and therefore minimize overall emissions.

5.3.4 Industrial Activities and Localized Pollution

- **Industrial Emissions and SO2 Levels:** Industrial activities however returned a weak correlation with SO_2 concentrations at $r = 0.58$, $p < 0.05$. Imposing stricter emission regulations and cleaner production machinery will reduce industrial SO_2 output. Another thing that can be done is the establishment of shoulder areas for such high-emission industries from places densely populated so that risk to the public can be minimized (Jiang et al., 2022). Encouraging the use of renewable energy sources in industrial operations would also lessen sulfur dioxide pollution.

- **Seasonal Variations in Industrial Pollution:** Such issues correspond with pollution increases at peak industrial production. The slow seasonal variations in manufacturing output were also associated with fluctuations in SO2 levels. Increased fuel consumption due to high production levels at peak periods has increased emissions and worsened air quality (Wallington et al., 2022).
- **Regulatory Compliance and Cleaner Technologies:** Conforming to regulations and applying cleaner technologies will minimize their emissions. Encourage the industries to switch to renewable sources to cut down even further their SO2 emissions (Lopez-Aparicio et al., 2025). The government will offer incentives for adopting low-emission technologies which may mobilize a much faster adoption. Periodic air quality testing in the boundary of industrial zones can track progress and compliance tracking.

Figure 5.2: Deaths by Common Causes for Men

Year	Number of deaths	Of which:								
		malignant tumors	acute myocardial infarction	other ischemic heart disease	cerebrovascular disease	bronchitis, emphysema and asthma[b]	liver diseases	Covid19	motor vehicle accidents	intentional self-harm
Man										
2010	65 137	18,032	4 258	11,132	6,083	2,708	3,302	–	590	1,945
2011	63,883	17,990	4,013	11,219	5,804	2,783	2,963	–	548	1,847
2012	63,504	18,279	3,929	10,928	5 550	2,885	2,655	–	512	1,803
2013	61,894	17,815	3,636	10,999	5,427	2,913	2,391	–	476	1,588
2014	61,992	17,763	3,351	11,238	5,269	2,913	2,468	–	478	1,480
2015	63,545	17,655	3,359	11,241	5,448	3,413	2,371	–	540	1,391
2016	62,658	18,020	3,365	11,089	4,713	3,028	2,284	–	529	1,317
2017	64,025	17,716	3 250	11,581	4,960	3,292	2,296	–	537	1,241
2018	64,016	17,617	3 250	11,417	4,851	3 260	2,412	–	530	1,276
2019	62,843	17,241	3,301	11,286	4,981	3,321	2,362	–	515	1,158
2020	68,661	16,804	3 219	11,357	5 162	2,872	2,451	4,616	415	1,311
2021	77,099	16,181	3,447	11,426	4,887	2,606	2,594	12,839	489	1 203
2022	66,749	16,029	3 222	11,155	4,599	2,715	2,643	3,811	464	1,257
2023	62,731	16,355	3,091	10,776	4,446	2,877	2 207	983	415	1,242

Source: (KSH, 2025).

5.3.5 Air Pollution-Linked Respiratory Diseases and Mortality Trends

- Respiratory illnesses such as bronchitis, emphysema, and asthma, are responsible for the death of a consistent number of people every year due to long-term exposure to poor air quality. In 2023, 4,446 men as well as 4,194 women died due to these diseases (KSH, 2025). Identifying the pollution hotspot-facilitative deaths, can involve using QGIS-based spatial analysis, to integrate air quality data with land use statistics. Such allows for precise mapping of such high-risk areas with appropriate interventions of a public health nature.

Figure 5.3: Deaths by Common Causes for Women

Year	Number of deaths	Of which:								
		malignant tumors	acute myocardial infarction	other ischemic heart disease	cerebrovascular disease	bronchitis, emphysema and asthma [h]	liver diseases	Covid19	motor vehicle accidents	intentional self-harm
Woman										
2010	65,319	14,428	3 223	15,229	7,918	1,881	1,320	–	203	547
2011	64,912	14,680	3,072	14,926	7,565	2,060	1,213	–	194	575
2012	65,936	14,945	3,089	15,005	7,531	2 203	1,042	–	187	547
2013	64,884	14,933	2,883	14,586	7,401	2,378	933	–	185	505
2014	64,316	14,985	2,621	14,929	7 121	2,299	972	–	192	447
2015	68,152	15,137	2,669	15,738	7,052	2,853	935	–	194	479
2016	64,395	14,967	2,379	14,451	5,988	2,462	893	–	163	446
2017	67,649	15 128	2,508	15,306	6,424	2,818	947	–	191	393
2018	67,029	14,969	2,583	14,852	6,416	2,833	931	–	205	380
2019	66,760	14,771	2,398	14,685	6,507	2,941	941	–	205	392
2020	72,341	14,819	2,436	14,923	6,560	2,480	910	4 365	139	395
2021	78,522	14,412	2,612	14,491	5,847	2 177	981	11,999	156	358
2022	69,697	14,427	2,335	14,230	5,789	2 240	913	3,874	163	390
2023	65,445	14,643	2 199	13,417	5,522	2,544	826	810	150	351

Source: (KSH, 2025).

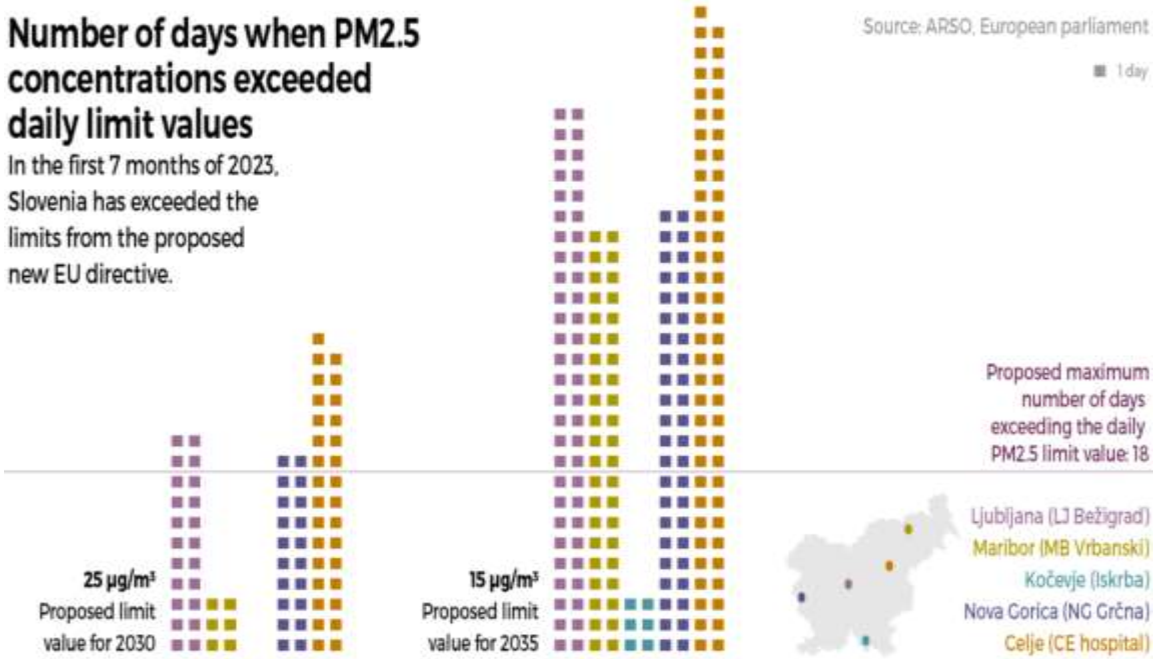
5.3.6 Cardiovascular Deaths Tied to Polluted Environments

- Acute myocardial infarction and other ischemic heart diseases figured above 25,000 in male deaths and 14,000 in female deaths in 2023 (KSH, 2025). Evidence is gradually linking fine particulate matter from emissions from industry and vehicles to the development of cardiovascular disease. Through QGIS spatial modeling overlaying pollution distribution patterns with cardiovascular mortality data, researchers have been able to establish relationships between high-emission zones and increased health risks. The geospatial approach presents opportunities for evidence-based urban planning and traffic management to minimize preventable death incidences.

5.4 Comparison with Other Urban Areas

To provide context for the air quality trends observed, Sopron was compared with two cities that greatly differ in geographical and economic contexts, namely the city of Ljubljana (Slovenia) and the capital city of Jakarta (Indonesia). This comparative exercise has the potential to highlight some good practices as well as areas for improvement. Learning from the policies and strategies adopted by these two cities may provide good insights for upcoming urban planning in Sopron (Jiang et al., 2022). In addition, contrasting transportation systems, industrial activities, and green infrastructure will help shed light on some of the particular factors inducing variations in air quality.

Figure 5.4: The Number of Days in Ljubljana when PM2.5 Exceeded Limits

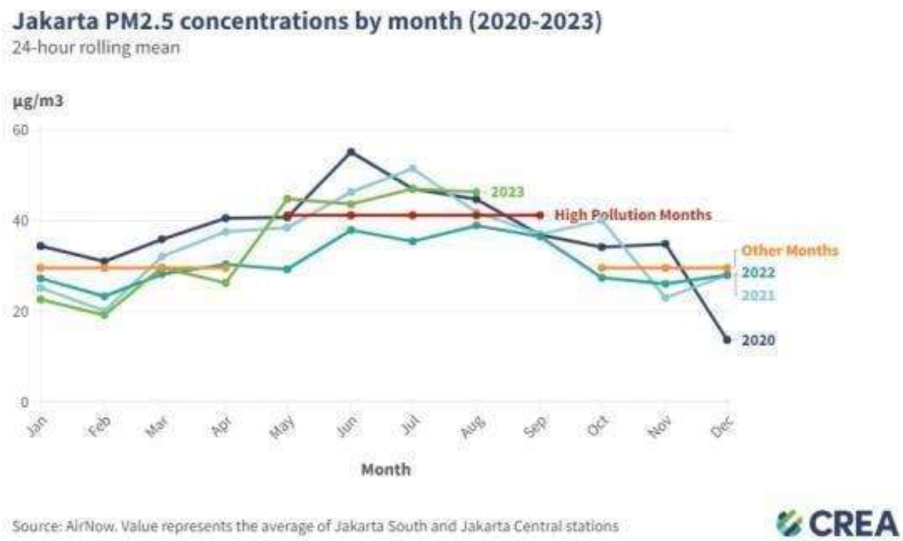


Source: (Radilovič et al., 2024).

5.4.1 PM2.5 Levels

- **PM2.5 Levels Analysis:** The annual mean PM2.5 level for Sopron (12 µg/m³) is lower than that in Jakarta (57 µg/m³) but higher than in Ljubljana (9 µg/m³). From this, it is clear that though Sopron enjoys progress in air quality management, more needs to be done (Lopez-Aparicio et al., 2025). Addressing pollution sources such as traffic emissions and industrial activities would be beneficial in a PM2.5 reduction drive.
- **Sustainable Urban Planning, and Air Quality Enhancements:** The capital city awarded its clear air status to act towards heavy greening and a modern public transport system that curbs vehicular emissions. In contrast, Jakarta suffers from high PM2.5 levels due to significant road traffic congestion, industrial pollution, and seasonal haze arising from agricultural burning in nearby areas (Jiang et al., 2022). Implementing elements of Ljubljana's sustainable urban planning may help Sopron realize better air quality benefits.

Figure 5.5: Jakarta PM2.5 Concentration by Month from 2020 to 2023



Source: (CREA, 2023).

- **Sustainable Transportation, and Public Engagement:** Undertaking similar policies will greatly benefit Sopron, for enduring results. Instigating stringent vehicle emission standards and promoting alternate modes of transport will help alleviate pollution (Wallington et al., 2022). Besides, engaging the public with sustainable commuting options will produce a more conducive environment for better policy implementation.

5.4.2 NO2 Concentrations

- **Comparing NO2 Concentrations:** Sopron had NO2 concentrations (20 to 25 µg/m³) lower than those in Jakarta (45 µg/m³) but comparable to Ljubljana (22 µg/m³). Traffic management and public transport investments were instrumental in keeping NO2 concentrations down (Wallington et al., 2022). Further uptake of pedestrianization and encouragement of electric vehicles would lead to even greater reductions.
- **Pedestrianization, and Low-Emission Zones:** The success in reducing NO2 emissions has primarily been because of the pedestrian latitude permitted in the downtown areas of Ljubljana and the stringent regulations on low-emission zones. On the other hand, Jakarta faces elevated NO2 levels due to traffic congestion and the rampant use of motorcycles (World Bank, 2020). Any improvement in public transport infrastructure for Sopron, as has been done in Ljubljana, could contribute toward the lowering of NOx emissions.
- **Strengthening Emission Laws for NO2 Reduction:** Enforcement of stricter emission laws in Sopron could lead to more or less similar results. Stricter vehicle emission standards and enhanced electric mobility will reduce pollution further (World Bank, 2020).

Monitoring and enforcement efforts can be made more rigorous and effective to ensure compliance with air quality regulations.

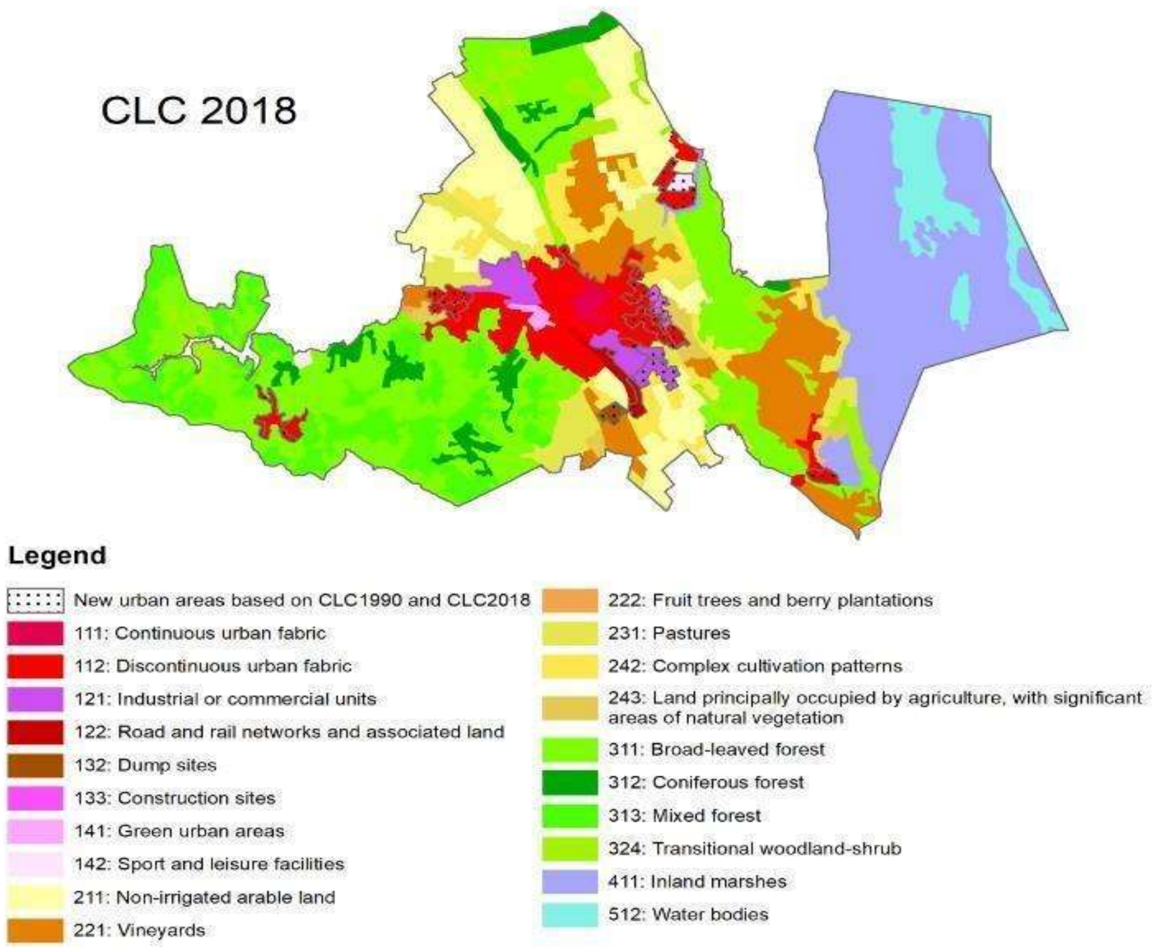
5.4.3 Urban Green Space Impact

- **Urban Green Space and Air Quality:** Among the cities, Ljubljana holds about 46% of urban green cover, which has a significant influence in terms of lower PM10 levels (14 µg/m³) compared to Sopron (18 µg/m³). Any expansion of green spaces at Sopron could alleviate the concentrations of PM. The incorporation of school forests and green corridors could establish better filters and benefit air quality in an overall way (Jiang et al., 2022).
- **Green Infrastructure Challenges in Jakarta:** Jakarta has only about 9% urban green cover which raises air pollution levels resulting in increased health problem exposure with a lower green infrastructure present. With this minimal green infrastructure, the air quality becomes part of the increased vulnerability of the city's population to health impacts from air pollution (Lopez-Aparicio et al., 2025). Expansion of these green spaces, similar to that in Ljubljana, could most probably turn out to be a long-term solution to improve air quality in Sopron.
- **Expanding Green Infrastructure:** More green infrastructure causes further increases in air quality. Rooftop gardens and tree-lined streets can further ameliorate air pollution (Wallington et al., 2022). Expansion of parks and restoration of natural areas within the city are also functional for long-term improvements in air quality.

5.5 QGIS Results and Discussion

This section presents the QGIS spatial analysis land use data, focusing on the urban expansion’s role in reshaping the region’s natural and agricultural landscapes. The evidence presents that forests and cultivated land in the region have been significantly transformed by a discontinuous urban fabric and industrial zones (Ahmed et al., 2024). Such shifts impinge directly on air quality since land cover loss reduces pollutants' absorption and filtration capacity. These findings reinforce the necessity for integrated urban development strategies that enhance environmental sustainability and air quality management.

Figure 5.6: CORINE Land Cover (CLC) Output for Sopron in 2018



Source: (European Environment Agency, 2020).

5.5.1 Urban Expansion from Natural Land

Urban transition into the natural environment recorded a variety of transitions, as detected by the QGIS analysis most notable being the transformation of broad-leaved forests (21.86 ha) representing 68.7% and mixed forests (0.014 ha), which is 0.044%, into discontinuous urban fabric in Sopron. These changes show a gradual pattern of land consumption accelerated by population growth and infrastructure demand (Darabos et al., 2024). The replacement of these ecologically rich landscapes by urbanization detracts from local air quality and environmental resilience.

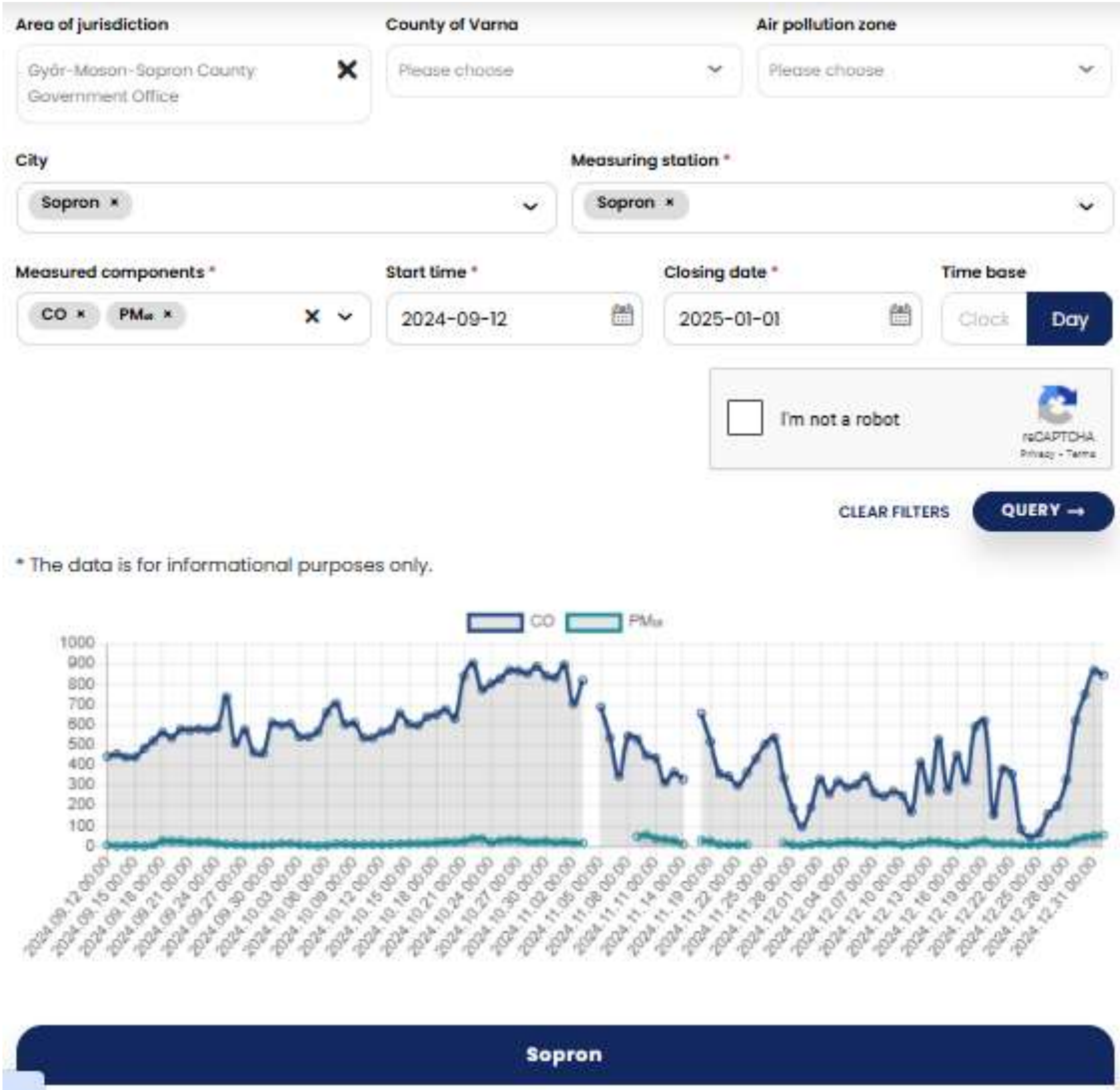
- **Loss of Forest Cover:** The conversion of 21.86 ha of broad-leaved forest and some areas of mixed forest into urban land constitutes a huge loss of tree cover and a natural carbon sink. The forest filters much of the airborne pollutants such as nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and particulate matter (PM) (European Environment Agency, 2025c). Hence, their degradation could facilitate the rise of pollutants in surrounding urban areas.

- **Environmental Influence on Local Climate:** Natural vegetation areas hold great powers of moderation over local temperature and humidity and serve as buffers to the urban heat island effect. Ács et al. (2021) further underscore that the change of these lands into the built environment would likely diminish local evapotranspiration rates while raising surface temperatures, aggravating air quality. Such effects may lead to atmospheric stagnation and less dispersion of pollutants.
- **Fragmentation and Biodiversity Depletion:** The scattered, albeit largely small-scale, elimination of forest areas fragment natural habitats. This ecological disruption not only affects biodiversity but also diminishes ecosystem services like air purification (Vasárus & Lennert, 2022). Therefore, small-scale destruction over time can exert an important cumulative adverse effect on air quality.

5.5.2 Air Quality Data Analysis for Sopron (September 2024 – January 2025)

- The daily measurements for carbon monoxide (CO) and particulate matter (PM_{10}), as given in the dataset for Sopron, reflect changes over time. CO concentrations fluctuate greatly during the day, and PM_{10} presents low levels. To further analyze these findings, QGIS will be used to investigate the spatial correlation of pollution levels along land use and traffic networks.

Figure 5.7: Graphical Portrayal of the CO and PM_{10} Concentrations in Sopron



Source: (HungaroMet, 2025).

5.5.3 Key Indicators to Assess Air Quality

- **CO Concentration Trends** – CO levels show significant daily fluctuations, on different days with sharp and abrupt peaks, particularly towards the end of the observed period. This suggests possible traffic or industrial emissions during that period. The maximum CO concentration was almost around 900 µg/m³, which indicates the possibility of pollution accumulation under some special meteorological conditions (HungaroMet, 2025). The mid-period decrease followed by another sudden peak increase is an indicator of possible variability in emissions sources or atmospheric dispersion factors. Using QGIS, this research overlays CO levels with urban transport and industrial zones to identify primary contributors to pollution spikes.

- **PM_{10} Levels** – These were consistently below the 50 μg/m³ detection level but revealed a lot of variations within them that suggested localized pollution episodes. Occasional minor spikes could denote short-term emissions from construction, road dust, or localized combustion. PM_{10} low concentrations on some days, especially mid-September, indicate very favorable meteorological conditions for pollutant dispersion (European Environment Agency, 2025b). One exercise of QGIS spatial mapping will correlate PM_{10} trends with the data on land use to screen probable sources and evaluate how the different parts could be contributing to variations in air quality.

Figure 5.8: The CO and PM_{10} Concentrations in Sopron

Sopron		
DATE	CO	PM_{10}
Limit values	- μg/m³	50 μg/m³
2024-09-12 00:00:00	444 μg/m³	6 μg/m³
2024-09-13 00:00:00	456 μg/m³	1 μg/m³
2024-09-14 00:00:00	441 μg/m³	2 μg/m³
2024-09-15 00:00:00	442 μg/m³	2 μg/m³
2024-09-16 00:00:00	485 μg/m³	1 μg/m³
2024-09-17 00:00:00	522 μg/m³	6 μg/m³
2024-09-18 00:00:00	562 μg/m³	27 μg/m³
2024-09-19 00:00:00	537 μg/m³	25 μg/m³
2024-09-20 00:00:00	578 μg/m³	25 μg/m³
2024-09-21 00:00:00	574 μg/m³	19 μg/m³
2024-09-22 00:00:00	581 μg/m³	21 μg/m³
2024-09-23 00:00:00	576 μg/m³	21 μg/m³
2024-09-24 00:00:00	588 μg/m³	13 μg/m³
2024-09-25 00:00:00	738 μg/m³	9 μg/m³
2024-09-26 00:00:00	509 μg/m³	8 μg/m³

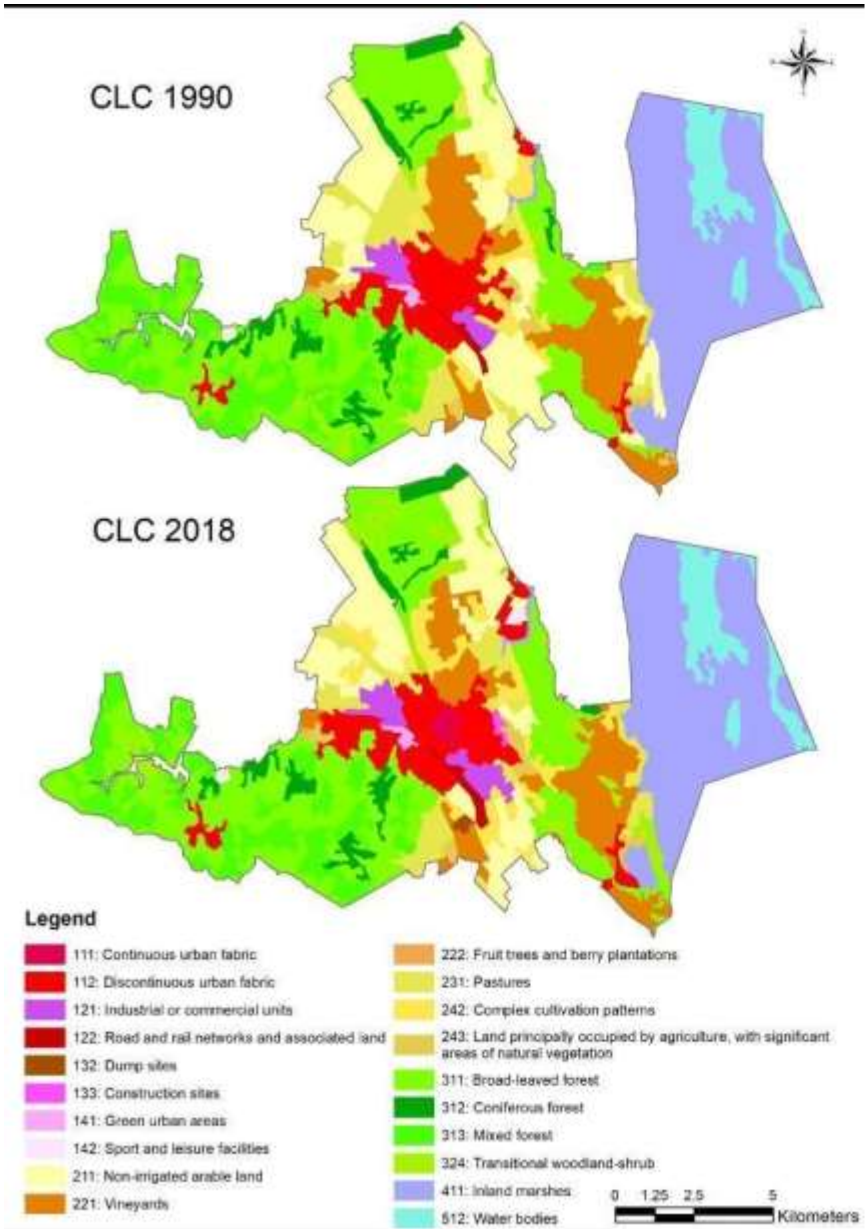
Source: (HungaroMet, 2025).

5.5.4 Methodology: Application of QGIS in Air Quality Analysis

The air quality dataset for Sopron, which gives the concentrations of carbon monoxide (CO) and particulate matter (PM_{10}), is indispensable for spatial analysis in this study. QGIS will be used for pollution evaluation of possible health impacts by visualizing both temporally and spatially the variations in air quality.

- **Spatial Analysis of Carbon Monoxide (CO) Trends Using QGIS:** According to the dataset, observed CO concentration values vary from a minimum of 441 µg/m³ to a maximum of 738 µg/m³ between September 12 and September 26, 2024, with an apparent increasing trend (HungaroMet, 2025). The highest level (738 µg/m³ on September 25) may point to pollution peaks attributed to either industrial activity or heavy traffic; alternatively, meteorological conditions could have contributed as well. Based on the spatial interpolation techniques available on QGIS, such as Inverse Distance Weighting (IDW) or Kriging, pollution hotspots will be located across various areas in Sopron. These geospatial insights will, therefore, assist in correlating CO levels with urban structures and traffic density for targeted intervention strategies.
- **Particulate Matter (PM_{10}) Mapping and Compliance Assessment:** Although PM_{10} concentrations never exceeded this threshold, and between September 18, 2024, with PM_{10} at 27 µg/m³, and September 13 and 16, when PM_{10} was as low as 1 µg/m³, the air was rather clean (HungaroMet, 2025). In QGIS, raster analysis is to be employed in the visualization of concentration gradients to show PM_{10} spatial dispersion patterns. The assignment of meteorological data layers in QGIS will also assist in establishing the influence of wind speed, temperature inversions, and/or atmospheric pressure on PM_{10} distribution.

Figure 5.9: Sopron's CORINE Land Cover for 1990 and 2018



Source: (European Environment Agency, 2020).

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Figure 6.0: The CO and PM_{10} Concentrations in Sopron

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Source: (HungaroMet, 2025).

5.6 Agricultural to Urban Transition:

Perhaps the most significant feature of the QGIS data is the transformation of agricultural land to discontinuous urban fabric-the conversion of non-irrigated arable land (97.35 ha), vineyards (29.79 ha), and complex cultivation patterns (124.15 ha) into this. The development is part of an extended urban encroachment on productive farmland, which could impact local food security as well as rural livelihoods (Vasárus & Lennert, 2022). Furthermore, as the movement from agricultural to built forms of land use increases vehicular traffic and construction-related emissions, it has resulted in worsening air quality in the area.

- **Reduction in Vegetative Surfaces:** Agriculture is like forests in some aspects, but not as effective. Even agricultural lands have some contribution to atmospheric filtering as they have crop cover and serve as soil carbon sinks (Szeberényi et al., 2022). Such large-scale transformation of vegetation land covers indicated by only 97.35 ha of arable land a great loss of vegetated land cover. With this, even the absorption of pollutants through photosynthesis and deposition processes decreases.
- **Soil Exposure and Dust Emissions:** The development and construction expose soil from what used to be agricultural land and add particulate matter (PM10 and PM2.5) to the atmosphere. Soil top disruption and earth movements usually increase airborne dust levels, especially in dry seasons (Szeberényi et al., 2022). It leads to poor air quality for the surrounding residents. Early urbanization phases usually cause such impacts, typical to the land transition analysis described.
- **Urban Sprawl and Rising Vehicle Emissions**: Stretched discontinuous urban fabric in an erstwhile agricultural field is an indicator of low-density building. Poor access to public transport is common with such layouts and hence contributes to higher car dependency and, therefore, localized vehicular emissions. It causes more accumulation of NO2 and CO within areas that are less in green buffer zones.

5.7 Agricultural to Industrial Land Use Change:

Another critical land use change identified in the QGIS data is the transformation of non-irrigated arable land (52.26 ha) and complex cultivation patterns (20.16 ha) into industrial or commercial units: those that consist of more than 70 ha. This development is indicative of an increasing demand for industrial infrastructure, often at the expense of agricultural output and green space. This also is typically followed by increased emissions from industrial activities and transportation, which would contribute considerably to localized ambient air pollution and environmental degradation.

- **Air Pollution from Industrial Activity:** Industrial zones have been recognized based on the emissions of fine particulates, VOCs (volatile organic compounds), and many more pollutants. Replacing agricultural land with industrial use introduces new stationary sources of emissions without or with unknown short- and long-term impacts on regional air quality. QGIS was so successful in this transition, more substantial for air quality monitoring.

- **Changes in Land Surface Properties:** The nature of industrial development is to render construction surfaces impermeable and use building materials that are effective heat absorbers and retainers, which serve to establish thermal hotspots (Szeberényi et al., 2022). Such hot areas tend to induce alterations in wind patterns and temperature inversions into the area, causing air pollutants to be trapped low on the ground. Thereby, implicated communities could suffer from deterioration in the quality of air and adverse health impacts.
- **Loss of Green Buffer Zones:** Agricultural lands have often served as buffer zones between urban cores and industrial centers. The conversion of agricultural lands for industrial use weakens these vegetative barriers that otherwise would have performed a service in mitigating dust, odor, and emissions (Sopron City Council, 2023). Results coming from QGIS, therefore, bring home the importance of zoning policies able to create and preserve environmental buffers for air quality.

5.8 Minor But Cumulative Changes

Some transitions might be small, when in terms of area, such as pasture (0.06 ha) or fruit trees (0.0014 ha) becoming transformed into urban or industrial land. However, these incremental changes, over time, cannot be said to remain insignificant. These cumulative changes, demonstrable in QGIS results, may lead to ecologically fragmented areas, with biodiversity loss and minor increases in air quality degradation when considered at larger scales (Vasárus & Lennert, 2022).

- **Microclimatic Changes:** Even those green patches of minimal size play a significant role in stabilizing the urban microclimate by moderating local temperature and adding moisture to the air. The continued degradation of such features may alter the climate at the neighborhood level, thus affecting air dispersion and pollution accumulation (Szeberényi et al., 2022).
- **Compounding Urban Footprint:** These small land use changes reflect a broader pattern of incremental urban growth that collectively expands the urban footprint. This growth increases energy consumption, transportation needs, and associated emissions, particularly when urban sprawl is not managed through integrated land-use planning (Darabos et al., 2024).
- **Invisibility in Policy Monitoring:** Small land cover changes are often overlooked in environmental policy and urban planning (Vasárus & Lennert, 2022). However, their aggregation, as revealed in QGIS spatial analysis, underscores the necessity for detailed monitoring to maintain air quality standards and preempt environmental degradation.

5.9 Total Land Cover Summary and Implications for Air Quality

The areas represented by discontinuous urban fabric (971.07 ha) and industrial/commercial units (227.66 ha) speak volumes about the expanse of urban land within the study area. Such increased urbanization, corroborated by QGIS, has a direct correlation with heightened emissions from transport, construction, and industrial activities, contributing primarily to the degrading state of the air quality (Darabos et al., 2024).

- **The Dominance of Urban and Semi-urban Land Uses:** Urban and industrial uses presently occupy over 7% of the total analyzed land area (16,899 ha). When considered in the context of regional air quality, this is an appreciable number, for those areas act as those spots with the concentration of pollution owing to their high activity and low levels of natural filtration (Vasárus & Lennert, 2022).
- **Vegetation Loss across Categories**: Broad-leaved forests (3969.49 ha), mixed forests (1470.02 ha), and coniferous forests (578.89 ha) have shown a major share in nature's vegetation which is experiencing pressure from encroaching urban development. The reduction of the area covered by such ecosystems ultimately means a lesser number of trees for sequestering CO_2 and pollutants reflected in air quality (Sopron City Council, 2023).
- **Significance of Green Urban Planning:** With a meager **37.35 ha** of green urban zones relative to almost **1200 ha** of urban or industrial, such denotes insufficient green infrastructure. Parks, urban forests, and vegetated corridors are invariably required to mitigate pollution and improve air quality (Szeberényi et al., 2022). Urban planning should instead consider providing more such spaces to balance the emissions due to ever-expanding urban developments.

Chapter 6: Policy Recommendations, and Mitigation Strategies

6.1 Sustainable Urban Planning Approaches

Urban sprawl and land use conversion should be mitigated through sustainable planning principles such as compact development and transit-oriented design together with more rigorous environmental reviews. From 2013 to 2023, urban expansion converted natural and agricultural lands into more than 360 ha of space and disturbed the local environment in its capability to regulate air quality while polluting it more in developing areas. Integration of green buffers with stricter control of land conversion should be instigated for the overall long-term sustainability of the environment (Vasárus et al., 2024).

6.1.1 Compact, Mixed-Use, and Transit-Oriented Development

The compact and transit-oriented development has been proven to be the most effective strategy for urban planning since it centralized housing, jobs, and services close to public transport. Tóth and Ferenczi (2024) denote that retailers and services are close to housing, dramatically reducing the use of private transport. Between 2013 and 2023, urban expansion changed over 360 hectares of natural and agricultural land, undermining the ecological air-regulating function and increasing the load of pollutants. Compact planning also helps to conserve these green zones while fostering much more efficient sustainable and healthier communities.

- **Vertical and Mixed-Use Zoning:** This would therefore ensure the vertical and mixed-use zoning of Sopron, with residential, commercial, and civic spaces all included within a single footprint, thus reducing land consumption. This, however, would promote walkability, reduce dependency on private car use, and thus lesser footprints of carbon per capita (Peterson, 2024). Thereby, it would also bring people closer to services, therefore, cutting down long movements upfront, as well as creating a platform for supporting sustainable transportation modes. Thus, this would create a far more efficient, healthier, and greener urban landscape for Sopron.
- **Transit-Oriented Development Hubs:** Ideally, high-density housing and related facilities should be located neighborhood-like to major transit lines. Houria et al. (2024) underscore that this will ensure that Sopron has greater transportation access to buses and trains. Moreover, it will subsequently carry more trips by public transit rather than by car and hence reduce traffic emissions. Therefore, cleaner air and less congestion should be created in the future, enhancing urban mobility while subsequently supporting sustainable transportation modes and an even more environmentally friendly urban environment for all.
- **Infill and Redevelopment Incentives:** Such tax credits or density bonuses would be granted for buildings in already developed areas, which will prevent such buildings from expanding greenfield sites. European Environment Agency (2023) explains how such would bolster Sopron’s capability to avert city sprawl through discouragement of greenfield areas, thus, preserving the natural space. Redevelopment of existing properties

would also bring back the aging infrastructure into greener and more efficient alternatives. Hence the strategy would harness sustainable growth while improving the overall environmental resilience of the city.

6.1.2 Green Buffers and Stronger Environmental Review

Though green buffers and strengthened environmental review systems are equivalent strategies to prevent air quality degradation and facilitate sustainable urban expansion, vegetative buffers reduce pollution exposure to immediate residential areas. Notably, high and mid-altitude forest conversions, alone above and beyond forest and mixed-vegetation conversions, resulted in a loss of more than 61 ha of green cover, including 21.86 ha of broadleaved forest and 39.24 ha of semi-natural land, to urban development, thus weakening the natural pollution filtration (European Environment Agency, 2025a). These measures are very crucial for good urban environment resilience and habitability and encourage responsible urban growth while ensuring that not much is lost in the name of clean air and natural assets.

- **Urban Tree Belts and Buffer Zones:** Sopron can install a series of tree rows and vegetation in between the two busiest highways in the city and between the third factory and residential houses to act as a separate physical barrier from airborne pollutants. According to the European Environment Agency (2025b), these green walls will absorb CO_2, filter particulate matter, and improve air quality. In addition, cooling of urban areas and noise pollution in heavily dense zones will be achieved. All these measures would improve environmental and public health within the city.
- **Comprehensive Environmental Assessments:** EIA models that require both air quality modeling and health risk evaluations would serve to make less painful informed decisions. This will ensure the developments reduce their environmental footprints early in the planning stage (HungaroMet, 2025). Strong EIAs foster transparency and public trust in urban projects.
- **Post-Development Air Quality Audits:** This necessitates that post project completion comparison takes place with regard to environmental standards. Such an accountability tool will help reveal problems that may not arise during planning, and furnish data from the real world to guide future urban planning decisions (Jankó et al., 2022).

6.2 Green Infrastructure and Air Quality Improvement

Green infrastructure provides for improvements to air quality and mitigation of urban heat isolation. The very presence of natural systems allows cities to address their air pollution through the absorption of harmful chemicals and additional cooling. The townspeople of Sopron have witnessed around 8% of urban green area loss, which diminishes its ability to alleviate air pollution and defend itself from temperature extremes (Lopez-Aparicio et al., 2025). Restoration and development of green infrastructure, including urban forests, vertical gardens, and wetland systems, should serve as the focus of urban planners to naturally detoxify pollutants such as $PM_{2.5}$, NO_2, and O_3 (Jiang et al., 2022).

- **Urban Forests and Tree Canopies:** The tree canopy coverage of Sopron should be added to and otherwise enhanced. Trees fulfill valuable functions by absorbing CO_2, filtering out particulate matter, and generally cooling down the developed areas (Jankó et al., 2022). Increasing green space reduces air pollution and the heat island effect, therefore improving public health and environmental conditions.
- **Vertical Gardens on Buildings:** Encouraging vertical gardens installations on buildings will help mitigate the loss of ground-level green areas. These gardens provide aesthetic value and help clean the air by filtering pollutants and aiding natural cooling (Jiang et al., 2022). By integrating vertical green spaces into resident and commercial buildings, Sopron can ameliorate its urban landscape while responding to environmental issues.
- **Wetland Restoration and Development:** Restoration of wetland areas beyond urban zones is important in air quality improvement and stormwater management. Wetlands filter water and air polluted with substances like nitrates and heavy metals in nature (Lopez-Aparicio et al., 2025). They also moderate temperatures and foster diversity, making the urban environment of Sopron itself more resilient and sustainable.

6.3 Transportation Policies, and Emission Control

As urbanization grows, so does the reliance upon private vehicles; thus, emissions from transport continue to be a prime reason for air pollution. Current NO_2 concentrations near large intersections regularly exceed 30 $\mu g/m^3$ during peak hours, directly associated with traffic congestion and inefficient vehicular flow (HungaroMet, 2025). The strategies to mitigate the situation should include expanding electric mass transit, establishing car-free zones, and smart traffic management systems to minimize exposure to harmful emissions in high-traffic zones.

- **Expansion of Electric Public Transit and Car-Free Zones:** Sopron should consider investment in electric buses and trams to reduce emissions from public transport and designate car-free zones in highly trafficked areas. These initiatives would not only lower levels of NO_2 and particulate matter, but would also foster sustainable mobility and therefore improve urban air quality as a result of walking, cycling, and cleaner transit initiatives (Lopez-Aparicio et al., 2025).
- **Smart Traffic Management and Promotion of Active Transportation:** Developing intelligent traffic management systems along with constructing infrastructures for cycling and walking will optimize vehicle flows, decrease congestion, and reduce emissions. Active transportation can be encouraged for use through lanes dedicated to it and improvement in pedestrian area safety would considerably alleviate the dependence on private car mobility (Radilovič et al., 2024). Thus, such would create an effect on public health and the environment by enhancing sustainability in the urban landscape.

6.4 Technological Innovations for Air Quality Monitoring

Technology innovation in air quality monitoring is instrumental to the aspect of real-time information and effective response to pollution control measures. In summer, for instance, ozone

(O_3) went up to about 60 µg/m³ in Sopron, which mainly resulted from emissions of vehicles and industry (HungaroMet, 2025). By investing in real-time monitoring systems, satellite-based sensors, and data-derived modeling of pollution, Sopron will have precise actionable insights into trends of health and air quality risks. Such technologies will facilitate active gas quality management and timely interventions.

- **Real-Time Air Quality Monitoring and Satellite Sensors:** Sopron should have stations monitoring the air quality in real-time across the city and satellite sensors for complete coverage. These technologies could facilitate the tracking of pollutants both in urban and remote areas and provide essential data for quick response by makers and the public when faced with hazardous events or in the management of pollution regionally (HungaroMet, 2025).
- **Data-Driven Pollution Modeling:** Spanning the atmospheric quality modeling and monitoring will put Sopron in a better position to predict future trends and pinpoint susceptible areas. The patterns might also simulate value-added scenarios, such as the creation of green spaces or changes in traffic, thus enabling evidence-based decisions in introducing interventions aimed at environmental changes before becoming hazardous (Jankó et al., 2022).
- **Public Access to Air Quality Data:** Real-time air quality data should be made available to the public via mobile apps or online platforms to increase awareness within the community. This transparency promotes healthier behavior, such as using public transportation or limiting outdoor activities on high-pollution days while creating an informed citizenry that supports environmental goals (Vasárus & Lennert, 2022).

6.5 Community Engagement and Awareness Programs

Public participation is an imperative for the success of any air quality policy. From 2013 to 2023, public exposure to PM2.5 in Sopron decreased from 18 to 12 µg/m³—an encouraging trend not only attributed to regulations but also to rising public awareness and behavioral changes (Vasárus & Lennert, 2022). Initiatives led by the community, like local air monitoring, environmental education in schools, and green volunteer programs, can further consolidate this progress by instilling a culture of environmental responsibility.

- **Local Air Quality Monitoring and Public Awareness Campaigns:** Sopron should promote citizen participation in air quality monitoring, providing portable sensors to help citizens track pollution levels. Szeberényi et al. (2022) aver that campaigns on public awareness through media will nurture a sense of environmental responsibility, inform the public about the health impacts of air pollution, and encourage eco-friendly approaches to aid in cleaning the air.
- **Environmental Education and Green Volunteer Programs:** Bringing air quality awareness into school curricula will educate future generations on sustainable practices, while green volunteer programs—including tree planting and urban gardening—will

involve residents in active environmental stewardship (Radilovič et al., 2024). Such endeavors will strengthen the ties of the community and foster a sense of long-term environmental stewardship for a healthier urban environment.

Chapter 7: Conclusion, and Future Research Directions

7.1 Summary of Key Findings

The study addresses a plethora of strategies put in place to ameliorate air quality in Sopron, with an emphasis on urban planning, green infrastructure, transportation policies, and technological advances. The loss of green spaces emerged as a huge threat, adding to heavy reliance on private modes of transport that have become a major factor in escalating air pollution levels. Major findings suggest that answering these challenges will call for the combined use of innovation solutions to cover areas such as green infrastructure, public transport enhancement, and real-time air quality monitoring.

- **Urban Planning and Green Infrastructure:** The study identified that urban planning strategies, such as expanding green infrastructure, are pivotal for maintaining and improving air quality. Air pollution intensified by the loss of green spaces, especially in high-traffic zones, can be mitigated by the introduction of urban forests, vertical gardens, and green buffers.
- **Impact of Private Vehicles on Air Quality:** The increased reliance on private modes of transportation has, until now, hugely contributed to increasing air pollution along major road networks, especially at peak hours (Szabados et al., 2023). The study highlights the necessity to promote alternative transport modes, such as electric public transit and transit-oriented development, for emission reduction and promoting sustainable transportation.
- **Technological Innovation for Air Quality Monitoring:** Real-time air quality monitoring systems with satellite sensors and pollution models are one of the major recommendations identified. These technologies can provide accurate, real-time data to manage air quality, allowing rapid response to hazardous events and enabling policymakers to make evidence-based decisions on the protection of public health.
- **Community Engagement and Public Awareness:** The study stresses developing community engagement through air-quality monitoring programs and public awareness campaigns. Involving people in local efforts to monitor air quality with portable sensors and fostering discussion around pollution's health impacts can give citizens a sense of ownership of their environment and support sustainable practice activities that would improve air quality in Sopron.

7.2 Implications for Policy and Planning

The study emphasizes the need for Sopron to consider air quality and environmental health in urban planning policies. The loss of green space and increasing reliance on private vehicles has worsened air pollution in the city and quantifies the need for sustainable urban management practices (Vasárus et al., 2024). Local authorities of Sopron must therefore endeavor to have all future urban planning, transportation policies, and zoning processes conform to these recommendations while creating a healthier urban environment.

- **Integration of Green Infrastructure in Urban Planning for Sopron:** The study highlights the need for green infrastructure to be considered within the context of urban planning. Installing green buffers or strips, urban forests, and green rooftops can all help mitigate air pollution, promote human health, and lower the urban heat island effect, making this well worth including in Sopron's zoning regulations and urban development plans for the achievement of long-term environmental sustainability.
- **Promotion of Sustainable Transportation Policies within Sopron:** The study suggests that the city should develop transportation infrastructure that prioritizes cleaner, more efficient transportation. Electric public transport should be actively promoted, while private vehicle use should be discouraged, given that the recommendations in this outcome intend to include the establishment of Transit Oriented Development (TOD) as a labeling vehicle for smog reduction, with an accompanying reduction in congestion (Tóth & Ferenczi, 2024).
- **Data-Driven Decision-Making Enhancement in Urban Planning:** An applicable tool in urban planning and policy-making involves integrating real-time monitoring of air quality with satellite-based sensors. This would enable prompt response to pollution events, aid in tracking the success of the measures implemented, and adjust urban planning choices based on actual data (Peterson, 2024).
- **Mobilizing Multi-Stakeholder Cooperation for Sustainable Urban Development**: A successful urban planning process involves participation by all stakeholders such as the local government, businesses, environmental groups, and residents. Such participation in decision-making would encourage dialogue among these parties, in addition to ensuring that there is indeed a place for the input of all parties involved, in the process of policy development toward making air quality and sustainability measures for improvement in Sopron more holistic and inclusive.

7.3 Recommendations for Further Research:

Future research is needed to comprehend the longer-term consequences of air quality strategies for public health and the urban resilience of cities as a whole, particularly regarding cities like Sopron. The following research themes will help optimize air quality management efforts and steer future directions in policy development:

- **Long-Term Impacts of Air Quality Improvement Strategies:** Future studies must address the long-term implications of urban air quality improvement strategies on public health, especially within such rapidly urbanizing areas as Sopron (Peterson, 2024). Understanding such benefits could include an outline of health benefits resulting from this intervention, such as reduced incidence of respiratory diseases, cardiovascular effects, and other conditions related to pollution, thus providing justification for such intervention and enabling it to be improved in the future.

- **Intervention Effectiveness in Diverse Urban Contexts:** Assessing specific interventions for their effectiveness in diverse urban contexts will require research into the effectiveness of such technologies as satellite-based sensors and electric public transit systems (Houria et al., 2024). Policymakers in Sopron and other cities would, then, be able to learn how these interventions work in different ecosystems, thus making it possible to tailor their strategies to local air quality problems and urban terrains.
- **Models of Community Engagement for Sustainable Behavior Change:** Understanding the place of community engagement in changing behavior towards sustainability is crucial. There is a need for intensive research on how citizen involvement, public awareness campaigns, and local air quality monitoring programs will improve public support for air quality policies (Jankó et al., 2022). Models that are understood well in encouraging community activity in the area of the environment will, therefore, strengthen efforts of Sopron in improving air quality in the long run.
- Economic Implications of Green Infrastructure and Sustainable Transport: Further research must also focus on the economic impacts of green infrastructure and sustainable transport policies in Sopron. Job creation potential in the green economy, long-term savings in health care costs due to improved air quality, and the financial advantages of attracting eco-conscious tourism and investment are just some of the assessments this might entail (Lopez-Aparicio et al., 2025).
- **Comparative Analysis of Urban Air Quality Management Models**: A comparison of air quality management strategies in various cities, especially common in Central and Eastern Europe, would provide critical lessons for Sopron (Jiang et al., 2022). Studying how other cities with similar demographic and environmental characteristics have managed with success to improve air quality can inform and speed the process for Sopron in evoking best practices in planning and policy.

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9.0 Appendices

Appendix A: 9.1 Raw Data and Additional Figures

Key Land Cover Transitions Based on CORINE 1990 and 2018 Data.

From	To	Area (ha)	Relevance
Broad-leaved forest	Discontinuous urban fabric	21.86	Natural to Urban
Land principally agriculture + nat. vegetation	Discontinuous urban fabric	39.24	Semi-natural to Urban
Non-irrigated arable land	Discontinuous urban fabric	97.35	Agricultural to Urban
Vineyards	Discontinuous urban fabric	29.79	Agricultural to Urban
Pastures	Discontinuous urban fabric	0.06	Minor
Mixed forest	Discontinuous urban fabric	0.014	Tiny, but forest loss. Natural to Urban
Complex cultivation patterns	Discontinuous urban fabric	124.15	Agricultural mix to Urban
Non-irrigated arable land	Industrial or commercial units	52.26	Agriculture to Industry
Complex cultivation patterns	Industrial or commercial units	20.16	Agricultural mix to Urban
Fruit trees and berry plantations	Industrial or commercial units	0.0014	Tiny

Land Cover Transition Matrix of CLC 1990 and 2018.

	Code_18																				
code_90	111	112	121	122	132	133	141	142	211	221	222	231	242	243	311	312	313	324	411	512	Grand Total
112	0.45%	5.17%	0.00%	0.00%		0.10%	0.00%		0.00%	0.00%	0.00%	0.00%	0.00%	0.02%	0.00%	0.00%	0.01%		0.00%		5.75%
121		0.00%	1.33%	0.02%			0.00%		0.00%			0.00%									1.35%
122		0.00%	0.00%	0.32%					0.00%												0.32%
141		0.00%					0.22%														0.22%
142								0.11%							0.00%	0.00%	0.00%				0.11%
211		0.58%	0.31%	0.14%	0.01%	0.00%		0.00%	8.94%	0.35%		1.50%	1.39%	0.13%	0.03%	0.10%		0.33%	0.05%		13.85%
221		0.18%			0.02%				0.10%	7.75%	0.00%	0.12%	1.01%	0.00%	0.05%	0.00%		0.33%			9.57%

222										0.00%	0.05%			0.01%	0.00%						0.06%
231		0.00%	0.00%						1.39%	0.00%		2.70%	0.08%	0.00%	0.00%	0.00%	0.00%	0.38%	0.13%		4.68%
242		0.73%	0.12%		0.11%	0.00%		0.16%	0.11%	0.25%		0.15%	1.63%	0.00%	0.00%	0.00%		0.00%	0.00%		3.27%
243		0.23%				0.08%			0.00%	0.03%	0.00%	0.01%	0.00%	0.90%	0.06%			0.00%	0.00%		1.30%
311		0.13%						0.00%	0.00%	0.00%		0.00%	0.00%	0.02%	21.15%	0.07%	0.57%	1.54%	0.00%		23.49%
312								0.00%	0.00%						0.34%	3.04%	0.01%	0.03%			3.43%
313		0.00%						0.00%				0.00%	0.00%		1.10%	0.12%	6.96%	0.52%			8.70%
324									0.00%			0.00%	0.00%		0.35%	0.00%	0.46%	0.00%			0.81%
411		0.00%						0.00%	0.00%	0.00%		0.00%	0.00%	0.01%	0.10%			0.17%	18.76%	0.00%	19.04%
512																			0.00%	4.06%	4.06%

Grand Total	**0.45%**	**7.02%**	**1.76%**	**0.47%**	**0.15%**	**0.17%**	**0.22%**	**0.27%**	**10.54%**	**8.38%**	**0.05%**	**4.48%**	**4.11%**	**1.08%**	**23.18%**	**3.32%**	**8.02%**	**3.32%**	**18.94%**	**4.06%**	**100.00%**

Row Labels	Sum of Area_Ha
Broad-leaved forest	3969.5
Complex cultivation patterns	552.8
Coniferous forest	578.9
Discontinuous urban fabric	971.1
Fruit trees and berry plantations	9.8
Green urban areas	37.4
Industrial or commercial units	227.7
Inland marshes	3218.5
Land principally occupied by agriculture, with significant areas of natural vegetation	219.9
Mixed forest	1470.0
Non-irrigated arable land	2340.5
Pastures	791.0
Road and rail networks and associated land	53.4
Sport and leisure facilities	18.0
Transitional woodland-shrub	137.3
Vineyards	1616.9
Water bodies	686.8
Grand Total	16899.3

Appendix B: 9.2 Air Quality Measurement Standards

- **Ground-Based Monitoring Stations:** For monitoring (PM 10, PM 2.5), sulphur dioxide (SO_2), nitrogen oxides (NOx), and carbon monoxide (CO).
- **Mobile Air Quality Sensors:** In measuring different air quality parameters at various points in time.
- **Low-Cost Sensor Networks:** Cheap air quality monitoring equipment used in densely populated urban settings.
- **Satellite Series from Google Earth Pro** Tracking Urban Growth and Its Impact on Air Quality, Identifying Industrial and Traffic-intensive Zones, Monitoring Green Space and Vegetation Deforestation
- **Using Land Use Statistics for Air Quality Assessment:** Correlation Between Land Use and Pollution Sources, Modelling Air Pollution Dispersion, Mapping and Modelling Air Pollution Dispersion in QGIS

Abbreviations

AQI: Air Quality Indexes

CLC: CORINE Land Cover

EEA: European Environment Agency

EU: European Union

IDW: Inverse Distance Weighting

LEZ: Low-Emission Zones

NO_2: Nitrogen dioxide

NO_x: Nitrogen oxides

O_3: Ozone

$PM_{2.5}$, PM_{10}: Fine particulate matter

QGIS: Quantum Geographic Information System

SO_2: Sulfur oxides / sulfur dioxide

TOD: Transit Oriented Development

VOCs: Volatile organic compounds