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COMPARISON OF AIR QUALITY AND NOISE POLLUTION BETWEEN TWO SLOVENIAN REGIONS

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Industry and increasing traffic congestion significantly affect the quality of the living environment in many parts of Slovenia. Residents in these areas are often exposed to elevated noise levels and air pollution, consisting of a complex mixture of gases and particulate matter. Long-term exposure to these factors is associated with an increased risk of developing respiratory diseases such as asthma and chronic obstructive pulmonary disease (COPD), as well as cardiovascular diseases, and can also impact brain function, skin and eyes. Exposure to noise above 55 dB can cause sleep disturbances, reduce concentration, and increase stress and anxiety. This study compared air quality and noise pollution in two industrially significant towns, Naklo (Upper Carniola) and Ptuj (Styria). Both towns are recognized as industrial areas located in close proximity to residential areas. Noise levels and particle number concentrations were measured using portable sensors during weekdays and working hours to assess environmental conditions and their potential impact on the local population. Elevated noise levels and the presence of particulate matter of varying sizes were observed in both towns. The study emphasizes the importance of understanding regional differences in air and noise pollution. It also underscores the need for sustainable industrial practices and careful spatial planning, which can help improve the quality of life in urban areas and surrounding industrial zones.

1. Introduction

In many environments, particularly in regions undergoing rapid urbanization and industrialization, exposure to air pollution and noise is steadily increasing (Altıntop et al., 2024). Environmental influences encountered throughout life, encompassing a wide range of chemical, physical and biological factors, collectively constitute the so-called exposome. Air pollution and noise pollution are key components of the exposome, significantly contributing to the overall burden of disease and impacting public health (Cacciatore et al., 2025). Noise, or sound pollution, is defined as unwanted or excessive sound that adversely affects the health and well-being of humans and other organisms. Industry represents a major source of noise.
The World Health Organization identifies thresholds of 55 dB (A) Lden (day-evening-night level, averaged over 24 hours) or 50 dB (A) Lnight (night-time averaged) as levels above which significant health effects may occur (Chen et al., 2024). Air pollution is defined as a phenomenon that harms ecosystems and disrupts normal conditions for human life and development when certain substances in the atmosphere exceed

specific concentrations (Bai et al., 2018). It originates from both natural sources, such as volcanic eruptions and wildfires, and anthropogenic activities, predominantly agriculture, industrial processes, and transport, including aviation, road traffic, and the combustion of fossil fuels. Air pollution is a complex mixture of gases and fine particles known as particulate matter (PM). Due to their harmfulness, PM10 and PM2.5, which largely originate from multiple sources, including combustion processes, traffic emissions, resuspension of dust, and industrial activities, are of particular concern (Ivan et al., 2025). Exposure to these particles is associated with an increased risk of cardiovascular and respiratory diseases, as well as higher mortality (Cacciatore et al., 2025).
Systematic reviews and meta-analyses indicate that inhalation of PM2.5 not only causes acute increases in blood pressure but also contributes to the development of chronic hypertension.

Other studies have linked these particles to insulin resistance, obesity and thrombosis, which can trigger atherosclerosis and other cardiovascular events (Münzel et al., 2020). Similarly, noise pollution has significant adverse effects on human and animal health. It is estimated that noise exposure in Europe affects more than 100 million people, contributing to approximately 12,000 premature deaths and over one million years of healthy life lost annually.

Exposure to traffic noise reduces quality of life and is associated with an increased risk of cardiovascular disease and sleep disturbances (Münzel et al., 2020; Chen et al., 2024; Park et al., 2026). Noise pollution and air pollution often co-occur, potentially leading to cumulative increases in health risks (Adegboye et al., 2023). The most vulnerable population groups include individuals living in densely populated areas, children, and older adults (Münzel et al., 2020).

The adverse effects of air pollution are also reflected in climate change, as they influence weather patterns and global temperatures (Chen et al., 2024). The co-occurrence of air and noise pollution, particularly in urban and industrial environments, underscores the need for comprehensive public health risk assessments that consider their combined contribution, rather than addressing them separately (Adza et al., 2023).

The aim of our study was to compare two industrially burdened and densely populated areas of two Slovenian regions. We analyzed air pollution in terms of particulate matter and assessed noise levels originating from industrial sources and heavy traffic. We also examined the presence of residential areas in close proximity to industrial activities and evaluated the conditions for suitable living near industrial facilities. Through this study, we aimed to contribute to a more comprehensive assessment of environmental risks in industrially impacted areas and, in the long term, to support more informed spatial planning. The development of measures to reduce environmental burdens, along with the implementation of sustainable industrial practices, is essential for improving the quality of life in such areas.

2. Methodology

2.1 Location

The study was conducted in two towns located in two Slovenian regions with significant industrial activity (Styria and Upper Carniola). Measurements were carried out in Ptuj and Naklo (Figure 1), where a combination of industrial facilities and high traffic density may significantly affect the quality of life.

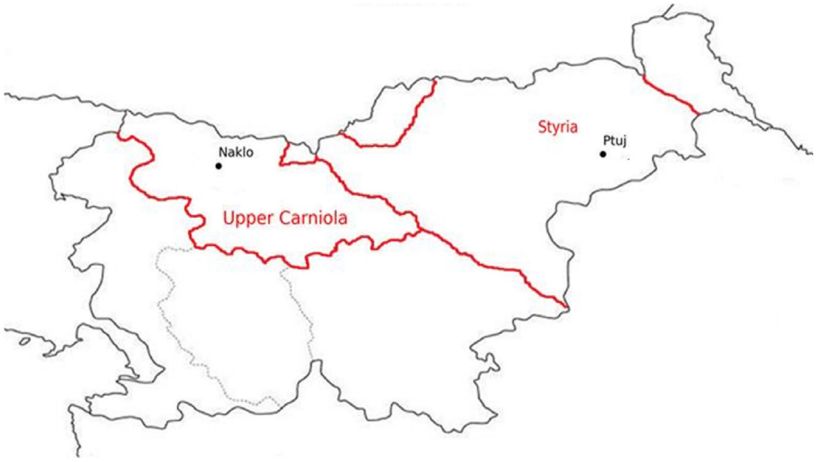

Figure 1: Map of Slovenia showing the towns of Ptuj and Naklo, both characterized by significant industrial activity. The regions (Upper Carniola and Styria) are indicated with a red line

Measurement locations were selected using the SPIRIT Invest Slovenia online database, managed by the public agency SPIRIT Slovenija. This publicly accessible information system provides an overview of industrial, economic, and business zones across individual municipalities. It includes data on the location, size, infrastructure, and designated land use of these zones, and offers valuable insight into the spatial distribution of industrial activities for investors, companies, and researchers. In Ptuj, two locations were selected: the Industrial Zone Ptuj (right bank of the Drava River) and the Economic Zone Ptuj (left bank of the Drava). In Naklo, measurements were conducted in a comparable central industrial and business zone located in the southern part of the town.

Measurements were conducted between October 30 and November 18, 2024. Noise levels and particle number concentrations were measured simultaneously on weekdays in the morning hours, between 8 and 11 AM. Measurements were conducted under stable weather conditions for later comparison across all locations. The weather ranged from partly cloudy to clear, with no rainfall recorded at least three days prior to measurements at each site. Temperature ranged between 8 °C and 15 °C.

2.1.1 Description of the industrial zones

The Industrial Zone Ptuj (right bank of the Drava River, Figure 2) is a small and compact industrial area located slightly outside the city center. The zone is adjacent to a smaller residential settlement, a railway line, and agricultural areas. The most prominent company in the area is Perutnina Ptuj, which operates silos at this location. Other businesses in the zone are engaged in printing, road construction and maintenance, and carpentry. Traffic in this area is relatively dense and consists predominantly of passenger vehicles.

Figure 2: Area of the Industrial Zone Ptuj (right bank of the Drava River). The measurement site is indicated by an arrow

The Economic Zone Ptuj (left bank of the Drava River, Figure 3) is an industrial and business area located near the city center of Ptuj. In this zone, industrial activities are interspersed with residential areas. On the outskirts, there is a railway connection to other towns. Traffic consists predominantly of passenger vehicles, with a smaller proportion of freight vehicles. The factories in this area manufacture CNC components, bearings, seals, clutches, belts, chains, and other industrial products.

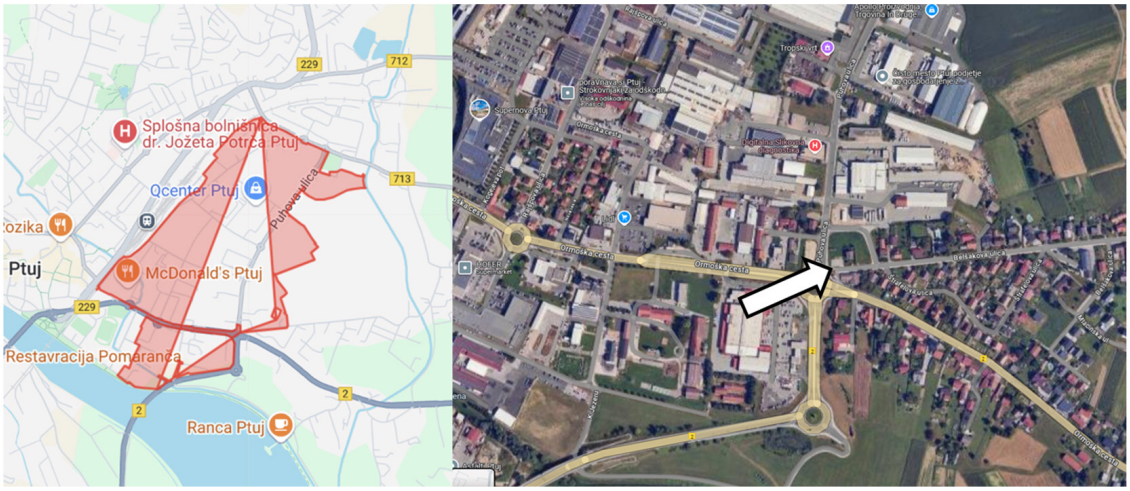

Figure 3: Area of the Economic zone Ptuj (left bank of the Drava River). The measurement site is indicated by an arrow

The Naklo industrial zone (Figure 4) is a large and extensive industrial area located along the main access road, south to southeast of the town. Its development began in 1978, and it plays a key role in the Upper Carniola. The zone hosts companies whose products and services reach beyond the region, exerting significant economic impact both nationally and internationally. Predominant activities include trade and logistics, construction and environmental services, specialized small enterprises, and institutions such as laser technology company, the Veterinary Institute, and healthcare facilities. The two most prominent Slovenian companies in the zone are Mercator and Merkur. The industrial zone developed in a location with a favourable transport connection, close to the motorway and a railway line. Traffic is relatively dense and consists of both passenger and freight vehicles.

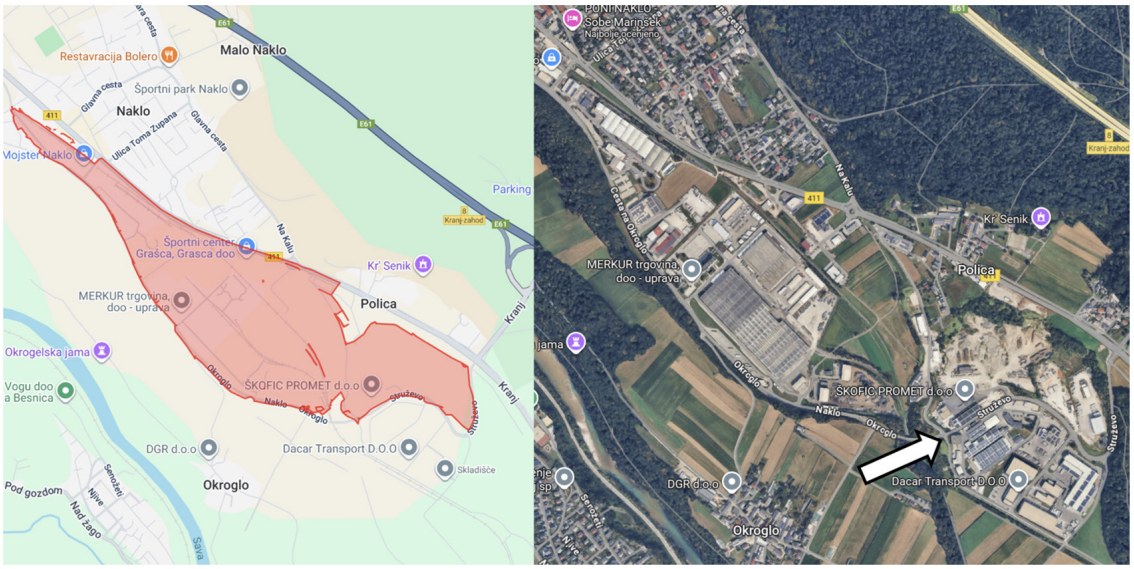

Figure 4: Area of the Naklo Industrial Zone. The measurement site is indicated by an arrow

2.2 Measurement Procedures

Noise measurements were performed using the Decibel X: dB Sound Level Meter software. Each measurement lasted 30 s, and 10 measurements were taken simultaneously at each location. The average sound level value was then calculated from the collected data. Measured values represent short-term equivalent sound levels (Leq) and are not directly comparable to regulatory Lden indicators.

Particulate matter measurements were conducted using the Lighthouse HANDHELD 3016 meter. Each measurement lasted 5 minutes. 15 measurements were performed per location on the same day. The device measured the number of particles in one cubic meter of air for the following sizes: 0.3 µm, 0.5 µm, 0.7 µm, 1 µm, 2 µm and 5 µm (Viegas et al., 2015). In addition to the number of PM for each size, the device recorded atmospheric temperature and relative humidity. Particle measurements were performed in an uncontrolled environment, where it was not possible to regulate all external parameters.

3. Results and discussion

The results presented below provide insight into how the industrial activity, combined with traffic influence environment in these regions. The measured data on particulate matter (PM) and noise levels were compared across the industrial zones of the selected towns.

Noise measurements revealed differences between the studied locations, as shown in Figure 5. The Economic Zone Ptuj (left bank of the Drava River) recorded an average noise level of 65.8 dB, with a peak value of 74.2 dB. In the Industrial Zone Ptuj (right bank of the Drava River) lower values were observed, with an average of 58.4 dB and a peak of 64.3 dB. The Economic Zone Ptuj (left bank of the Drava River) exhibit slightly higher noise levels, likely due to the coexistence of industrial activity and residential areas. In comparison, the Naklo Industrial Zone exhibited the highest noise levels, with an average of 68.4 dB and a peak reaching 87.7 dB, which reflects the larger scale of industrial activity and the higher traffic volume in the area. The higher noise levels observed in Naklo Industrial Zone reflect the larger scale of industrial activity and the greater volume of heavy traffic in the area.

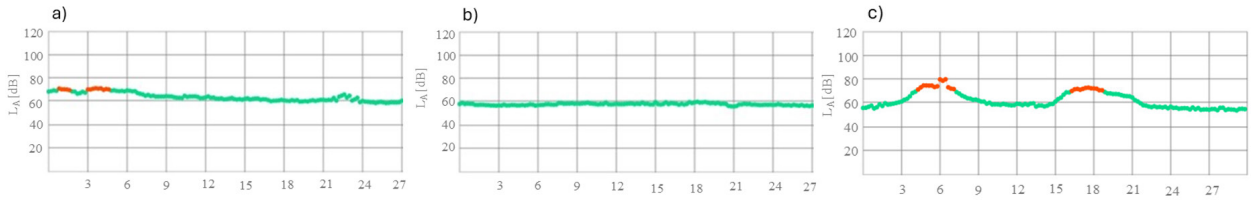

Figure 5: Noise levels as a function of time for the selected industrial zones: a) Economic Zone Ptuj (left bank of the Drava River), b) Industrial Zone Ptuj (right bank of the Drava River), and c) Naklo Industrial Zone

In Slovenia, environmental noise limit values are defined by the regulation "Uredba o mejnih vrednostih kazalcev hrupa v okolju", which classifies areas into four noise protection zones. The investigated locations fall within Zones III and IV. Zone III primarily includes residential areas, where the day-evening-night limit value is set at 65 dB, while Zone IV comprises commercial and industrial areas with a permissible limit of 75 dB (Ministry of the Environment, Climate, and Energy, 2025). In most cases, the measured noise levels remained below the applicable limit values; however, occasional peaks were recorded that approached or exceeded the permitted thresholds. At the Economic Zone Ptuj (left bank of the Drava River), the measurement site was located at the boundary between Zones III and IV; therefore, the stricter limit value of 65 dB was used as a reference. In this case the average noise levels exceeded the limits prescribed for residential areas (65 dB), while peak values approached those permitted for more industrial zone (75 dB). Measurements conducted in the Industrial Zone Ptuj (right bank of the Drava River), classified as Zone IV, showed that the average noise level did not exceed the limit value of 75 dB. In the Naklo Industrial Zone, which is also classified as Zone IV, the average noise levels did not exceed the limit value of 75 dB. Nevertheless, two pronounced peaks were recorded, reaching up to 87.7 dB, indicating an exceedance of the permissible limit value for this zone. However, it should be noted that the present measurements are based on short-term Leq values and therefore provide only an approximate comparison with Lden-based regulatory limits.

Figure 6 shows the particle number concentrations of different sizes in industrial zones in Ptuj and Naklo. In the Industrial Zone Ptuj (right bank of the Drava River), higher concentrations were observed for the smallest particles, reaching 1.9 · 108 /m3 at 0.3 µm and 1.3 · 107 /m3 at 0.5 µm. Concentrations for larger particle sizes were substantially lower, ranging from 2.2 · 106 /m3 at 0.7 µm to 0.4 · 105 /m3 at 5.0 µm. This distribution indicates a dominance of smaller particle size fractions, which can be attributed to industrial processes such as combustion and material processing, likely associated with facilities such as Perutnina Ptuj. In contrast, the Naklo Industrial Zone exhibited higher concentrations for larger particle sizes. While fine particle concentrations remained high, reaching 1.4 · 108 /m3 at 0.3 µm, larger particle sizes concentrations were notably elevated compared to Ptuj, reaching 2.7 · 106 /m3 at 0.7 µm, 0.8 · 106 /m3 at 1.0 µm, and up to 2 · 105 /m3 at 5.0 µm. Overall, concentrations for particles ≥ 0.7 µm ranged approximately between 105 and 106 /m3. This shift toward coarser particles is consistent with the characteristics of the Naklo Industrial Zone, which includes construction, logistics activities, and a higher proportion of heavy vehicle traffic, all contributing to particle generation. The Economic Zone Ptuj (left bank of the Drava River) displayed intermediate values across particle sizes. For fine particles, concentrations were 1.0· 108 /m3 at 0.3 µm and 0.76 · 107 /m3 at 0.5 µm, while larger particles ranged from 1.61 · 106 /m3 at 0.7 µm to 0.61 · 105 /m3 at 5.0 µm. These values reflect a mixed environment where moderate industrial activity coexists with residential areas and medium traffic density.

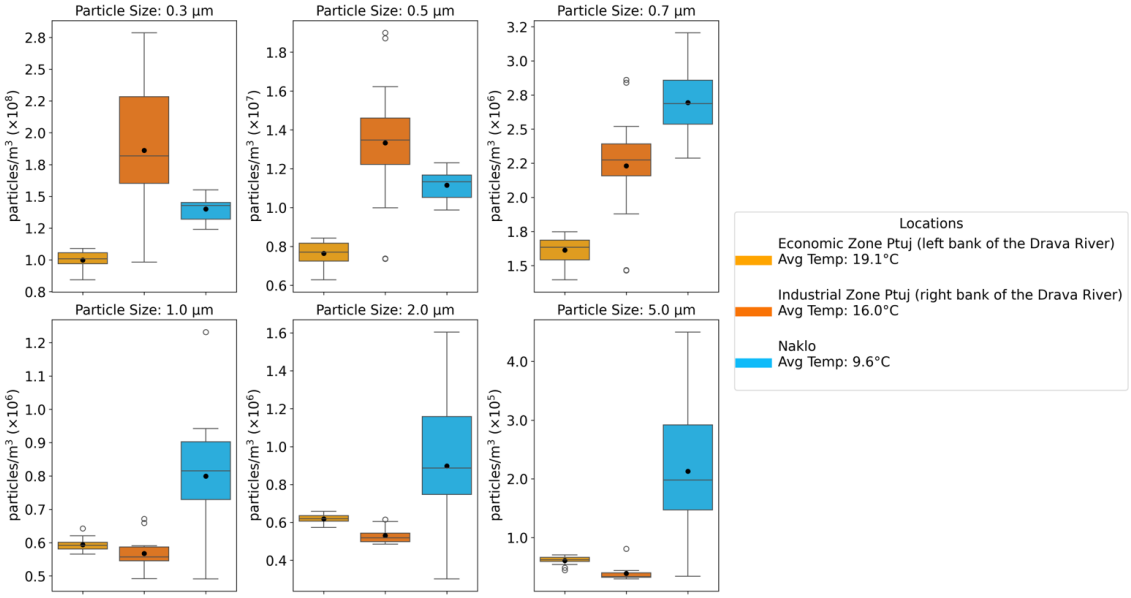

Figure 6: Comparison of particle number concentrations by particle size across the selected industrial zones

The impact of industrial activity on residential environments was also evaluated. In the Industrial Zone Ptuj (right bank of the Drava River), living conditions appear less favourable, as indicated by the relatively low number of residential buildings. In contrast, in the Economic Zone Ptuj (left bank of the Drava River), industrial facilities coexist with residential areas. Medium-to-high noise levels and elevated particle number concentrations present challenges for the quality of life of residents. In Naklo, the industrial zone is located on the outskirts of the town (south to southeast), where residential buildings are sparse, minimizing direct exposure to industrial pollution for local inhabitants.

Overall, the results (in Table 1) demonstrate that industrial activities and traffic influence both particle number concentrations and noise levels, with the type and scale of industry, as well as proximity to residential areas, playing a critical role in pollution exposure and living conditions of the residents.

Table 1: Mean values with standard deviations for particle number concentrations in the selected industrial zones.

Size of particles (µm)	Economic Zone Ptuj (left bank of the Drava River)	Industrial Zone Ptuj (right bank of the Drava River)	Naklo Industrial Zone
0.3	(1.00 ± 0.07)·108	(1.90 ± 0.50)·108	(1.40 ± 0.09)·108
0.5	(0.76 ± 0.06)·107	(1.30 ± 0.30)·107	(1.12 ± 0.08)·107
0.7	(1.61 ± 0.10)·106	(2.20 ± 0.40)·106	(2.70 ± 0.20)·106
1.0	(0.59 ± 0.02)·106	(0.57 ± 0.05)·106	(0.80 ± 0.20)·106
2.0	(0.62 ± 0.02)·106	(0.53 ± 0.04)·106	(0.90 ± 0.40)·106
5.0	(0.61 ± 0.07)·105	(0.40 ± 0.10)·105	(2.00 ± 1.00)·105

This study has several limitations. Noise measurements were performed using a smartphone-based application and represent short-term Leq values, which are not directly comparable to Lden indicators. Particle measurements were based on number concentrations rather than mass, limiting comparison with air quality standards. Despite this, the study provides useful comparative insights into environmental exposure across industrial zones.

4. Conclusions

The results of noise and particle number concentration measurements in two industrially and residentially significant towns indicate that both industrial activity and traffic contribute substantially to environmental burdens. Elevated noise levels and particle number concentrations were recorded at both selected locations, supporting the hypothesis that proximity to industrial zones poses a risk to the quality of life of humans and other organisms. The findings also confirm that noise and particulate matter pollution occur simultaneously and exert a cumulative effect. For this reason, they should be considered together rather than as separate units of analysis. Although the measured values were within the expected range for urban areas with industrial activity, the results highlight the need for continued monitoring of environmental parameters and the appropriate implementation of measures to mitigate impacts on human health and nearby ecosystems. The study thus underscores the importance of systematic planning and oversight in the spatial development of residential areas near industrial zones. Future studies should include long-term monitoring, calibrated instrumentation, and simultaneous assessment of mass-based particulate metrics to enable direct comparison with regulatory standards.

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