sciendo

Management Systems in Production Engineering

2025, Volume 33, Issue 4, pp. 568-575

Date of submission of the article to the Editor: 05/2025
Date of acceptance of the article by the Editor: 10/2025

DOI 10.2478/mspe-2025-0059

THE AIR POLLUTION MANAGEMENT IN THE CONTEXT OF LOCAL INDUSTRY AREAS LOCATION – CASE OF CZĘSTOCHOWA

Renata Stasiak-Betlejewska
Czestochowa University of Technology

Abstract:
The air quality assessment is performed in a division into zones, and each zone in Poland is assessed separately. Its result is the assignment of a class for individual pollutants. Poland remains in the forefront of EU countries with the most polluted air. The air quality management remains a pressing challenge in Poland, which consistently ranks among the European Union (EU) countries with the highest levels of ambient particulate matter pollution. Częstochowa, a medium-sized industrial and transport hub in southern Poland, represents an illustrative case where multiple sources of emissions converge. The city is characterized by a mixed-source profile that includes industrial emissions, transport-related pollutants, and household combustion for heating. The aim of the study presented in this paper is an analysis of the air pollution management in Częstochowa with a specific focus on the role of local industrial areas and their spatial distribution. Methodologically, the study combines data from national monitoring networks, EU air quality reports, and academic research with a comparative policy analysis. Paper identifies, analyses and assesses the level of air pollution quality for chosen city and indicates final recommendations for local communities that meet problems with polluted areas resulting from industry zones existence. The results reveal that while industrial areas contribute significantly to local emission hotspots, the seasonal dominance of household heating (so-called "low-stack emissions") and traffic congestion remain equally important contributors to overall pollution. Research findings indicate that management strategies must be multi-scalar, combining local, regional, and national interventions. In this context, an action plan for 2025-2035 has been proposed as the proposed solution for the identified problem. This strategy has been structured into three phases: short-term (2025-2027) interventions targeting residential heating and initial industrial audits; medium-term (2028-2031) strategies focused on district heating expansion and renewable integration; and long-term (2032-2035) transformations aiming for full alignment with World Health Organization (WHO) air quality standards and the development of sustainable industrial clusters. The study highlights that Częstochowa's future air quality improvements depend not only on technological modernization but also on governance, stakeholder engagement, and regional cooperation.

Key words: air pollution, quality, management, industry

INTRODUCTION

According to European Environment Agency reports a significant proportion of Europe's urban population lives in cities where EU air quality standards for the protection of human health are regularly exceeded. The air pollution is one of the most important factors that have huge impact on the human health and it generates economic costs, increase medical costs and it also reduce productivity by working days reduction. Air pollution is a local, pan-European and hemispheric issue, that results in the transfer of air pollutants released in one country to other countries. There are some three pollutants that are now generally recognised as the most significantly affecting human health such as: particulate matter, nitrogen dioxide and ground-level ozone [1].

Air pollution has negative influence on the human health and ecosystems, what was presented in Figure 1. Certain harmful air pollutants are emitted directly from vehicles, such as 'primary' particulate matter (PM) and nitrogen oxides (NOx). Others, such as ozone and 'secondary' PM, form in the atmosphere after emissions of precursor pollutants, including NOx and volatile organic compounds.
Different sources of pollution, including transport and non-transport sources, emit different types and ratios of pollutants [2].
Air quality has not always been the result of human-induced air pollutant emissions. It should be emphasized that there is no consistent linear relationship between decreasing emissions and observed air pollutant concentrations.

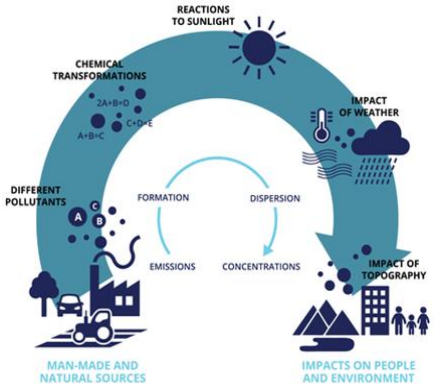

Fig. 1 Mechanism of the air pollution negative influence on the human health and ecosystems
Source: EEA 2020.

One of the more significant phenomena is the growing share of long-distance transport of air pollutants to Europe from other countries.
There are various sources of the air pollution, both anthropogenic and of natural origin [3, 4, 5]:

- burning of fossil fuels in electricity generation, transport, industry and households;
- industrial processes and solvent use, for example in chemical and mineral industries;
- agriculture;
- waste treatment;
- volcanic eruptions, windblown dust, sea-salt spray and emissions of volatile organic compounds from plants are examples of natural emission sources.

One of the long -term goals of the European Union is the desire to achieve the level of the air quality, which does not cause unacceptable concentrations having a negative impact on human health and thus increasing the risk of danger to human life and the natural environment. The European Union operates at many levels, seeking to achieve the above goal. This happens, among others, through: appropriate regulations, cooperation with the sectors responsible for air pollution, as well as cooperation with international, national and non -governmental authorities, as well as research. In 2013, the European Commission has implemented a proposed Air Quality Packet including new reducing funds.
The EU's air quality directives (2008/50/EC Directive on Ambient Air Quality and Cleaner Air for Europe and 2004/107/EC Directive on heavy metals and polycyclic aromatic hydrocarbons in ambient air) set pollutant concentrations thresholds that shall not be exceeded in a given period of time. In case of exceedances, authorities must develop and implement air quality management plans. These plans should aim to bring concentrations of air pollutants to levels below the limit and target values. There are also WHO guideline values are set for the protection of health, and are generally stricter than the comparable politically agreed EU standards [6, 7, 8].
According to European Directives, the air quality status should be maintained where it is already good, or improved. The risk posed by air pollution to vegetation and natural ecosystems is most important in places away from urban areas. The assessment of such risks and the compliance with critical levels for the protection of vegetation should therefore focus on places away from built-up areas. Air quality plans should be developed for zones and agglomerations within which concentrations of pollutants in ambient air exceed the relevant air quality target values or limit values, plus any temporary margins of tolerance, where applicable. Air pollutants are emitted from many different sources and activities [6, 7].
Air pollution is measured by European Environment Agency's with using European Air Quality Index which allows users can gain insights into the air quality of individual countries, regions and cities.
Europe has recorded a significant decrease in the emissions of many air pollution over the past decades, which has probably contributed to the improvement of air quality. Still, the concentration of the air pollution is high and thus the problems related to the quality of the air persist, especially in the city areas, in which air quality standards (ozone, nitrogen dioxide and particle particles) are often noted.
In the years 2010-2023, a decrease in industrial air pollution emissions was recorded in Europe (Figure 2). A decrease in greenhouse gas emissions (carbon dioxide (CO_2), sulphur oxides (SOx)) and other impurities (nitrogen oxides (NOx), solid particles (PM10) and heavy metals has been reported by a sector. During this period, the value generated by the industry for the European economy increased, which is associated with an increase in efficiency in terms of the indicator of the generated emission and production of the sector value [9].

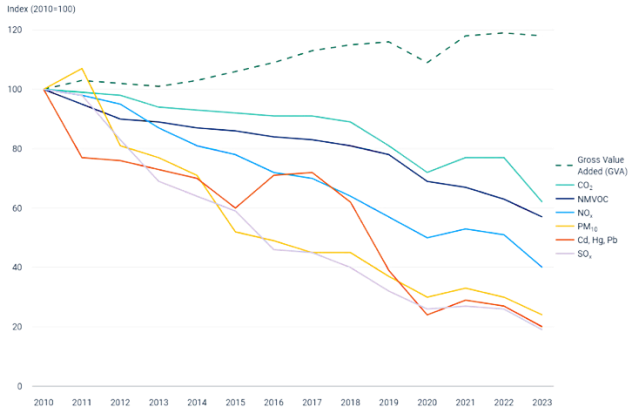

Fig. 2 Industrial releases of pollutants to air and economic activity in the EU-27
Source: EEA 2023.

Phenomena regarding the activity of the European industry cause the release of pollutants to the air, which is associated with the emission, among others: nitrogen oxides (NOx), particulate matter (in this case PM10), non-methane volatile organic compounds (NMVOCs) and heavy metals including cadmium (Cd), lead (Pb) and mercury (Hg). Between 2010 and 2023, industrial releases of heavy metals (Cd, Hg and Pb), SOx and PM10 decreased by over 75% in the European Union (Figure 3).
The observed reduction of industrial pollution emissions into the air partly results from the introduced European regulations, such as the EU Emissions Trading System and

the Industrial Emissions Directive. A reduced level of air pollution emissions is also associated with the introduction of modern energy efficiency technologies and limitations as well as the transfer of various production and energy-saving industries (such as textile or metal production) outside Europe. In order to reduce pollution emissions, EU industrial policy is aimed at switching to zero pollution, neutral climate industry based on a on circular material flows and the use of natural resources. Monitoring of release of air pollution is the key to tracking progress towards achieving text goals.

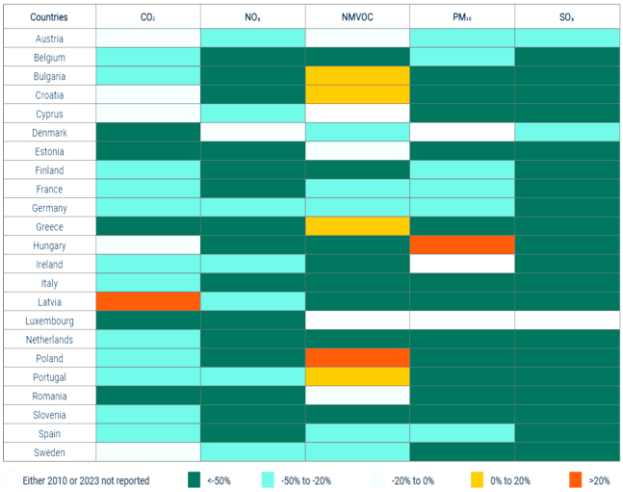

Fig. 3 Change of pollutant releases into air in EU-27 countries in the period 2010-2023
Source: EEA 2023.

Air pollution is one of the most critical environmental challenges in Poland, directly linked to industrial development, urbanization, and transport intensity.

According to the European Environment Agency, Poland is among the countries with the highest concentrations of particulate matter (PM10, PM2.5) and nitrogen oxides (NOx). The World Health Organization emphasizes that exposure to polluted air increases the risk of respiratory and cardiovascular diseases, which remain leading causes of premature mortality [1, 6].

The report of the Chief Inspectorate for Environmental Protection (GIOŚ) from the beginning of 2025 indicates a slow improvement in air quality in Poland, but the problem of low emission from solid fuel combustion in home furnaces is still significant. In recent years, Poland, despite some progress, still remains a country with one of the worst air quality in Europe. The air quality in the country is varied, with forecasts indicating the deterioration of the situation in the central and south-eastern part of the country due to poor wind, while the northern area is to have better quality. Reports on air quality in Poland in 2020-2025, published, among others By GIOŚ, they point to a slow improvement in the situation, although there is still a big problem with pollution, especially in regions such as Silesia and Lesser Poland, where there are cities with the worst air quality (e.g. Żywiec or Pszczyna). The air quality indicator (AQI) is used to assess the level of pollution, and WHO standards are still often exceeded, although regions that meet these standards, such as Słupsk, also appear [10].

The city of Częstochowa, situated in southern Poland, is an example of a medium-sized urban area that is heavily influenced by the presence of industrial zones. The concentration of metallurgy, heavy industry, and logistics infrastructure contributes significantly to local air pollution. This research focuses on assessing the air quality in Częstochowa in relation to industrial area locations, identifying main pollutant sources, and formulating recommendations for improved management practices and strategies for effective air pollution management.

The aim of the study presented in this paper is an analysis of the air pollution management in Częstochowa with a specific focus on the role of local industrial areas and their spatial distribution.

The relevance of this study lies in the need to understand how the spatial distribution of industrial areas influences the air quality and how local governments can align air quality management strategies with broader EU climate and environmental policies. Recent European directives, including Directive (EU) 2016/2284 on the reduction of national emissions of certain atmospheric pollutants (NEC Directive), impose obligations on member states to achieve significant emission reductions by 2030.

The research findings analysis points toward the necessity of elaboration and implementation of integrated management in the form of strategy that balances local industrial regulation, transport planning, and residential heating policies. The city's pollution levels remain above EU and WHO recommendations, with significant implications for public health. The presented recommendations provide a framework for sustainable air pollution management in industrially burdened urban areas. The paper includes elaborated strategy of integrated management within the policy that meet mentioned above EU and WHO recommendations.

RESARCH METHODOLOGY

The research methodology consisted of the following steps:

1. Literature review on the collection of national and regional reports on air quality (documents and reports of European Environment Agency, European Union and Polish Chief Inspectorate for Environmental Protection).
2. Data analysis that is based on the statistical analysis of air quality indicators for Częstochowa based on monitoring stations located within and near industrial zones.
3. Comparative evaluation – analysis of Częstochowa results against regional averages for the Silesian Voivodeship and EU reference values.
4. Impact assessment – identification of correlations between industrial activity and pollutant concentrations.
5. Recommendations – development of local policy guidelines and technical improvements to reduce the impact of industry on air quality.

The study is constrained by the limited number of monitoring stations in Częstochowa (two fixed and one mobile), which restricts spatial representativeness. Furthermore, industrial self-reporting of emissions may underestimate actual contributions. Despite these limitations, triangulation of datasets increases the robustness of findings.

Annual air quality assessments are key documents in the process of issuing and changing permits for the introduction of gases or dust into the air and integrated permits (they do not matter only in the installation application procedure due to the emission to the air).

According to art. 225 of the Environmental Protection Law In the area indicated in the annual assessment of air quality as an area of exceeding the air quality standard, the release of the permit (from a newly built or changed installation) for the introduction of a substance into the air for which the standard of air quality has been exceeded is possible only after conducting compensation proceedings, which ensures adequate reduction of existing emissions. In other words, if the new industrial installation or installation changed significantly is located on the abovementioned The area indicated in the annual assessment of air quality, in accordance with the Environmental Protection Law, will not obtain an emission permit against effectively conducted compensation proceedings. In practice, compensation proceedings are difficult to conduct, time-consuming and expensive. The knowledge of the location of the installation relative to mentioned areas of exceeding is therefore crucial in the investment process. Without conducting compensation proceedings, an environmental decision can be obtained and building an installation (or make a significant change), but you cannot obtain a permit specifying the conditions of using the environment, which in particular is a condition for putting the installation for use under Art. 76 of the Environmental Protection Act.

RESEARCH RESULTS AND DISCUSSION

Poland's air quality remains problematic, with 36 out of 46 zones in 2022 exceeding permissible levels of PM10 or PM2.5 (EEA, 2023). The dominant sources of pollution are domestic heating (coal-based), transport, and heavy industry.

Analyzed city, Częstochowa, belongs to the Silesian Voivodeship, one of the most industrialized regions in Poland.

Anthropogenic emission is the main source of air pollution in the Śląskie Voivodeship. In the field of PM10 and PM2.5 and Benzo (a) pyrene, the largest share is the emission from the municipal and daytime sector (surface emission), in the field of nitrogen oxides, this is the issue of industrial activities (point emission) and transport (linear emission), in relation to sulphur oxides, the greatest emission comes from industrial activities (point emission). Participation in the concentrations of pollution in the air in the voivodship also has an influx of emissions from Poland and Europe, and periodically also from Africa and Asia. The source of emission that affects the concentration of pollution, especially in areas directly adjacent to roads with significant traffic in the Śląskie Voivodeship, is road transport. Community pollution in the form of dust arises mainly as a result of abrasion of brakes, tires and road surfaces and pollution from the surface of the road, while nitrogen oxides are emitted from exhaust pipes. Road transport has a significant share in the total emission of nitrogen oxides in the analysed city voivodeship. The highest emission from the road transport sector occurs in the areas of large cities and along communication thoroughfare with the highest traffic of car traffic per day. In the Śląskie Voivodeship these are the A4 and A1 motorways. The Upper Silesian agglomeration is responsible for 32% of nitrogen oxides emissions, 32% PM10 dust and 32% PM2.5 dust on a voivodship. On a scale of the whole country, the Śląskie Voivodeship is responsible for about 10% of the issue of the abovementioned road transport pollution.

Industrial location in relation to residential zones plays a key role in shaping pollution exposure levels. Many industries are located in the Śląskie Voivodeship. Metallurgy, power plants, coke and mining have the largest share in dust pollution (GIOŚ, Chief Inspectorate for Environmental Protection).

Częstochowa covers an area of approximately 160 km² and is situated in the north of the Silesian Voivodeship. The city is traversed by major transportation corridors, including national roads and railway lines, and lies in a geographic depression that limits natural ventilation. Industrial activities are concentrated in specific zones, particularly Raków, where metallurgical operations are located, and Dźbów, which hosts manufacturing plants.

The analysed city is characterized by:

- the presence of heavy industry, including metallurgy and machinery production,
- dense road networks, increasing NOx and CO_2 emissions,
- residential heating based on fossil fuels, further worsening winter smog.

Częstochowa, located in the northern part of the Silesian Voivodeship, is a medium-sized city with a population of approximately 220,000. Historically associated with heavy industry, particularly metallurgy, machinery, and chemical processing, the city retains industrial facilities that are spatially interlinked with residential and commercial zones. This urban-industrial configuration increases the exposure of residents to emissions from both industrial and domestic sources.

The Częstochowa industry, traditionally based on metallurgy and textile industry, is currently characterized by the dynamic development of automotive, glass and fuel-energy industries. The city focuses on investments, offering attractive conditions, including location in the Katowice Special Economic Zone (KSE), as well as tax breaks. Currently, there are three dominated industries: automotive, glass and fuel-energy industries in Częstochowa. The number of business entities registered and operating in Częstochowa is around 26,700, including in the public sector 357 and in the private sector 26343.

Air quality in Częstochowa is a topic that is worth following on a regular basis, especially during the heating period. Municipal measuring stations, including those on the streets of Baczyńskiego and Stradom, regularly provide information on the concentration of suspended dust PM10 and PM2.5, which are the main components of air pollution. These harmful particles can lead to serious health problems, especially in people with respiratory diseases, children and seniors. Owing to data from such sources as Airly, the current concentration of pollutants in Częstochowa is visible.

Smog over Częstochowa is a problem that regularly intensifies in the winter. Combustion in furnaces and transport emissions contribute to deterioration of air quality, which results in higher concentration of suspended dust. Daily smog measurement in Częstochowa allows to assess when the concentration of harmful substances in the air achieves levels that can threaten health. Air pollution can cause coughing, eye irritation, and in the long run even increase the risk of cardiovascular and respiratory diseases.

Between 2015 and 2022, Częstochowa consistently exceeded EU limit values for PM10 and PM2.5. The highest concentrations were observed during winter, when residential coal combustion peaks. Annual averages of PM10 ranged between 40-55 μg/m³, compared to the EU annual limit of 40 μg/m³. PM2.5 concentrations averaged 25-35 μg/m³, far above the WHO guideline of 5 μg/m³. Data from Chief Inspectorate for Environmental Protection indicate that Częstochowa has seen a gradual decline in annual average PM2.5 concentrations since 2015 [11]. However, concentrations remain above WHO guideline levels (5 μg/m³) and frequently exceed EU annual limits in winter months (25 μg/m³ for PM2.5) [1, 12]. Peaks occur in period January – March, coinciding with domestic heating demand [13, 14]. Benzo[a]pyrene, a key carcinogen, exceeded the target value of 1 ng/m³ in all years of the study, with winter averages exceeding the target by 300-500%. This pollutant is strongly linked to domestic coal burning but also associated with industrial emissions from coke and metallurgical processes.

Industrial emissions in Częstochowa are spatially clustered in the northern and eastern zones of the city. These areas include steel processing, chemical industries, and manufacturing facilities. While modernization has reduced SO_2 emissions, particulate matter and NOx remain problematic, particularly near industrial-residential interfaces [15, 16].

Traffic-related NO_2 levels are highest along the national road DK1 and within the central districts. Although average levels are within EU limits, short-term peaks coincide with rush hours [10]. These emissions also contribute secondary particulate formation [17].

Household combustion remains the dominant source of PM2.5, especially in single-family housing areas using coal or wood. The municipal “anti-smog resolution” has stimulated some transitions, yet progress is uneven due to socio-economic constraints [18].

The location of industrial facilities within close proximity to residential neighbourhoods intensifies localized exposure risks. The absence of sufficient buffer zones and outdated emission abatement technologies contributes to hotspots. Enforcement of Best Available Techniques (BAT) remains a critical challenge [19].

Częstochowa exemplifies a “mixed-source” city: industrial emissions are important but often overshadowed by domestic heating during the winter [14].

This seasonal duality complicates management strategies, requiring both structural interventions (district heating, renewables) and behavioral changes (energy efficiency, fuel switching) [20].

Częstochowa is influenced by transboundary pollution flows from the broader Silesian region. This implies that local policies alone cannot secure compliance with WHO standards; regional coordination mechanisms are necessary [21].

The evidence points toward the necessity of integrated management that balances local industrial regulation, transport planning, and residential heating policies. Furthermore, alignment with EU Green Deal and Poland’s National Air Protection Program is indispensable [6, 22, 23, 24].

Data show that PM10 and PM2.5 concentrations in Częstochowa frequently exceed both EU annual and daily limit values. In 2022, annual average PM10 was 42 μg/m³, compared to the EU limit of 40 μg/m³, while PM2.5 averaged 28 μg/m³, exceeding the WHO guideline (5 μg/m³). Benzo[a]pyrene exceeded the target value by more than 300% in winter months [14].

Industrial emissions (mainly metallurgical plants in Raków district) account for 20-25% of PM emissions in Częstochowa, with significant contributions of SO_2 and NO_x. Proximity to residential areas leads to localized hotspots, particularly under low wind conditions. GIS mapping confirmed that monitoring stations located near industrial sites recorded consistently higher PM and SO_2 concentrations.

Figure 4 presents schematic map-style visualization of Częstochowa showing industrial zones (red squares) and residential areas (blue circles), annotated with approximate pollution intensity values (μg/m³).

Emission inventories indicate that industry contributes approximately 20-25% of particulate matter emissions, 35% of SO_2 emissions, and 30% of NO_x emissions in Częstochowa. Proximity analysis shows that monitoring stations near the Raków industrial zone reported systematically higher SO_2 and NOx concentrations compared to other stations.

The highest pollution concentrations were observed in the northern and eastern industrial zones of the city, particularly near steelworks and logistics centres. Air monitoring stations indicated that the residential districts closest to these industrial areas experience significantly higher pollutant levels than the city average.

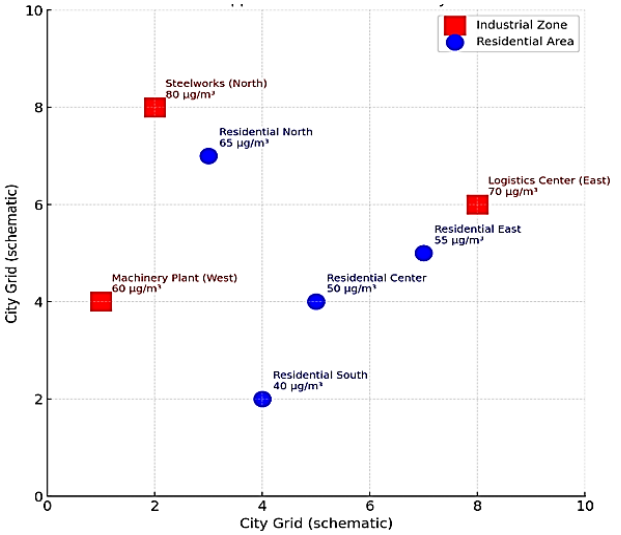

Fig. 4 Schematic Map of Industrial Zones and Residential Areas in Częstochowa with Approximate Pollution Intensity
Source: own study based on AQI presented in https://www.iqair.com/poland/silesia/czestochowa.

Winter months showed up to 3-4 times higher pollutant levels due to coal-based heating. However, summer peaks of SO_2 and NO_2 were associated with industrial activity. This suggests a combined impact of both industrial and residential sources. Częstochowa's air quality problems reflect the broader situation in Poland, where "low-stack" emissions from households dominate, but industry remains a relevant contributor. While EU directives require stricter emission standards, enforcement at the municipal level is uneven [25].

The location of the industry in close proximity to housing amplifies exposure risks. Previous studies in Upper Silesia confirm similar patterns [26]. Air protection programs in Częstochowa have focused mainly on reducing residential coal burning through subsidies for gas connections and renewables. However, industrial emissions require stronger monitoring and stricter integration with local land-use planning.

The study confirms that:

- PM10, PM2.5, and BaP exceedances remain chronic in Częstochowa.
- Industrial emissions account for up to one-quarter of PM loads and significantly affect local hotspots.
- Air management strategies must integrate industrial emission reduction with transport and residential measures.

Recommendations include:

- Establishing stricter industrial emission monitoring and reporting.
- Creating green buffer zones between industry and residential districts.
- Accelerating household coal-to-gas and renewables transition.
- Integrating industrial zoning policies into the local air protection plan.

To mitigate the negative impact of industrial zones on air quality in Częstochowa, the following measures are recommended [27]:

1. Technological modernization introducing stricter emission standards and promoting the use of best available techniques (BAT) in the industry.
2. Urban planning creating buffer zones of green infrastructure (trees, shrubs) between industrial areas and residential districts.
3. Air quality monitoring expanding the network of local monitoring stations, particularly in neighbourhoods adjacent to industry.
4. Transport policies promoting low-emission public transport and regulating heavy truck traffic near residential areas.
5. Public participation involving local communities in decision-making processes regarding industrial development and air quality management.
6. Renewable energy adoption incentivizing the transition from coal-based heating systems to renewable and clean energy sources.

As a supplement to the recommendation presented in the paper, it was proposed to implement in the analysed city a specific action plan for period 2025-2035 that support reducing the emissions of pollutants resulting from the presence of an existing industrial zone.

The Action Plan is presented as a narrative strategy framed within the context of environmental governance and sustainable development. It is structured into three chronological phases that reflect the progression from immediate interventions to long-term systemic transformation.

In the first phase concerning Measures (2025-2027), the priority is to tackle the most acute contributors to poor air quality – domestic heating and industrial compliance gaps. The municipality should accelerate the replacement of outdated coal stoves through expanded subsidies and enforce the regional anti-smog resolution. Simultaneously, industrial audits should be conducted to evaluate compliance with BAT requirements. Initial low-emission zones in the city centre would reduce transport-related NO_2. These measures correspond with EU NEC Directive 2020 interim targets.

The second phase (2028-2031) aims at systemic improvements. Expansion of district heating and natural gas networks should reach peri-urban areas. Industrial zones must integrate renewable energy technologies, such as photovoltaic arrays and biomass co-firing. Transport management should include electrification of public buses and incentives for electric vehicles. By 2030, the city should achieve compliance with EU PM2.5 limits (20 µg/m³ annual mean). This phase will require coordinated financing through EU Cohesion Policy funds.

The final phase (2032-2035 presented Long-term Transformation) envisions a structural transformation toward sustainable urban-industrial coexistence. By 2035, Częstochowa should aim to meet WHO's recommended PM2.5 annual guideline of 5 µg/m³. Industrial zones must transition into low-emission clusters with circular economy principles. Urban planning should emphasize green infrastructure, reducing urban heat islands and fostering air

dispersion. These measures align with the EU Green Deal's 2050 climate neutrality objective.

The phased strategy is expected to reduce premature mortality linked to air pollution by 20-30% by 2035, improve industrial competitiveness, and enhance quality of life. Challenges include financial constraints, social acceptance, and the need for regional policy coordination. However, Częstochowa can leverage its position as a medium-sized city to serve as a model for integrated urban-industrial air quality management in Central Europe.

Action plan recommend to: prioritize domestic heating replacement and industrial audits, implement low-emission zones to reduce traffic-related NO_2, measures align with EU NEC Directive 2020, expand district heating, integrate renewable energy in industrial zones, electrify public transport.

CONCLUSIONS

The case of Częstochowa demonstrates that air pollution management in medium-sized cities with industrial zones requires an integrated and multi-scalar approach. Częstochowa is influenced by transboundary pollution flows from the broader Silesian region. This implies that local policies alone cannot secure compliance with WHO standards; regional coordination mechanisms are necessary. Industrial area location is a critical factor, yet the interplay with transport and residential sources demands comprehensive governance. Future improvements will depend on the systematic implementation of phased measures targeting household heating, industrial modernization, and sustainable mobility.

The evidence points toward the necessity of integrated management that balances local industrial regulation, transport planning, and residential heating policies. Furthermore, alignment with the EU Green Deal and Poland's National Air Protection Program is indispensable. Częstochowa exemplifies the challenges faced by Polish cities where industrial zones directly influence air quality. The city's pollution levels remain above EU and WHO recommendations, with significant implications for public health. Addressing this issue requires a combination of stricter industrial regulation, improved urban planning, and active participation of local communities. The presented recommendations provide a framework for sustainable air pollution management in industrially burdened urban areas.

From a broader perspective, the Częstochowa case underscores the necessity of regional solidarity and cross-border collaboration in air quality governance. Transboundary emissions undermine local efforts and call for harmonized monitoring systems, joint emission inventories, and cross-regional mitigation programs. Without such cooperation, progress in single cities will remain constrained by the structural legacy of industrialization in Upper Silesia. Strengthening ties with EU institutions and leveraging EU funds for modernization projects are therefore strategic priorities.

The city's experience also highlights the socio-economic dimension of environmental management. Many households continue to rely on outdated heating systems due to affordability barriers, while industries face cost-intensive modernization challenges. Policies must therefore integrate environmental objectives with social justice mechanisms, ensuring that clean air strategies do not exacerbate inequalities. Subsidy programs for low-income households, incentives for small and medium-sized enterprises, and education campaigns on sustainable practices can play decisive roles in facilitating this transition.

In addition, the integration of technological innovation and data-driven tools offers a pathway to more precise and effective interventions. Expanded air quality monitoring networks, real-time pollution alerts, and advanced modelling of pollutant dispersion can enhance both governance and public engagement. Digitalization and smart city approaches can further support transport optimization, energy efficiency, and emission tracking, strengthening the city's adaptive capacity.

Looking ahead, resilience-building must become a guiding principle in Częstochowa's environmental policies. Climate change is expected to exacerbate air pollution episodes through heatwaves, altered atmospheric circulation, and increased energy demand. Preparing for these shifts requires long-term strategies that link air quality management to climate adaptation, circular economy principles, and regional sustainable development goals.

Finally, the study contributes to the wider body of research on medium-sized industrial cities, demonstrating that they face unique challenges distinct from large metropolitan areas or rural regions. Częstochowa illustrates that industrial heritage, urban form, and socio-economic conditions converge to create complex air quality issues that cannot be addressed through isolated interventions. Future research should therefore focus on comparative analyses across similar urban-industrial contexts, the effectiveness of multi-level governance frameworks, and the role of citizen participation in shaping sustainable transitions.

For policymakers, the findings provide actionable evidence on the importance of coordinating industrial regulation, residential heating programs, and sustainable transport strategies within a regional framework. For researchers, the case of the examined city air pollution opens avenues for interdisciplinary studies combining environmental science, urban planning, public health, and social policy. By bridging policy and academic perspectives, this study not only sheds light on the pressing challenges of air pollution but also outlines a pathway for medium-sized European cities to become laboratories of sustainable urban-industrial transformation.

REFERENCES

[1] European Environment Agency (EEA), "Air quality in Europe – 2023 report". Luxembourg: Publications Office of the European Union, 2023.
[2] European Environment Agency (EEA), "Air pollution: from emissions to exposure
[3] Infographic" (static) Nov 2020.
[4] Vallero, D. A., "Fundamentals of air pollution", Academic press, 2025, pp. 45-47.

[5] Han, S., Peng, D., Guo, Y., Umar Aslam, M., Xu, R., "Harnessing technological innovation and renewable energy and their impact on environmental pollution in G-20 countries". *Scientific Reports*, 15, 2236 (2025). https://doi.org/10.1038/s41598-025-85182-0
[6] Saxena, V. Water Quality, "Air Pollution, and Climate Change: Investigating the Environmental Impacts of Industrialization and Urbanization", *Water Air Soil Pollution*, 236, 73 (2025). https://doi.org/10.1007/s11270-024-07702-4
[7] EU Air Quality Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe, OJ L 152, 11.6.2008, pp. 1-44
[8] EU Air Quality Directive 2004/107/EC of the European Parliament and of the Council of 15 December 2004 relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air, OJ L 23, 26.1.2005, pp. 3-16
[9] WHO, 2006, Air quality guidelines: Global update 2005.
[10] European Environment Agency (EEA), "Industrial Reporting under the Industrial Emissions Directive 2010/75/EU and European Pollutant Release and Transfer Register Regulation (EC)", No 166/2006 – ver. 14.0 Mar. 2025.
[11] Główny Inspektorat Ochrony Środowiska Regionalny Wydział Monitoringu Środowiska w Katowicach, "Roczna ocena jakości powietrza w województwie śląskim. Raport wojewódzki za rok 2024", 2025.
[12] Chief Inspectorate of Environmental Protection (GIOŚ), "Annual Air Quality Assessment in Zones in Poland – 2022 Report", Warsaw: GIOŚ, 2023.
[13] World Health Organization, "WHO Global Air Quality Guidelines: Particulate Matter ($PM_{2.5}$ and PM_{10}), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide", Geneva: World Health Organization, 2021.
[14] A. Samek, "Seasonal variation of PM-bound polycyclic aromatic hydrocarbons in southern Poland and their relation to meteorological parameters," *Atmospheric Pollution Research*, vol. 7, no. 4, pp. 788-797, 2016.
[15] E. Widziewicz-Rzońca, J. Rogula-Kozłowska, K. Klejnowski, and A. Rogula-Kopiec, "PM2.5-bound polycyclic aromatic hydrocarbons in the atmosphere of Upper Silesia (Poland): Concentrations, sources, and health risk assessment," *Air Quality, Atmosphere & Health*, vol. 11, pp. 687-701, 2018.
[16] M. Kukuła, "Spatial differentiation of air pollution in Silesian voivodeship," *Environmental & Socio-economic Studies*, vol. 8, no. 2, pp. 47-57, 2020.
[17] P. Brzozowski and J. Badyda, "Long-term exposure to PM2.5 and PM10 and cardiovascular mortality in Poland," *International Journal of Environmental Research and Public Health*, vol. 16, no. 14, p. 2467, 2019.
[18] T. Holnicki, B. Kałuszko, and B. Nahorski, "Multi-scenario air quality impact assessment of urban traffic in Warsaw, Poland," *Transportation Research Part D: Transport and Environment*, vol. 36, pp. 167-182, 2015.
[19] A. Bartosz and P. Oleniacz, "Local air quality management in Poland: challenges and perspectives," *Ecological Questions*, vol. 31, no. 1, pp. 27-36, 2020.
[20] European Commission, Best Available Techniques (BAT) Reference Document for Large Combustion Plants. Luxembourg: Publications Office of the European Union, 2017.
[21] Zawada, M., & Szajt, M., "Application of statistical and econometric tools in the analysis of air pollution level on the example of Czestochowa", *Folia Oeconomica Stetinensia*, 2018, 18 (2), 145-164. https://doi.org/10.2478/foli-2018-0024
[22] OECD, "Air Quality and Health: Review of Evidence and Policy Recommendations", Paris: OECD Publishing, 2020.
[23] Ministry of Climate and Environment of Poland, "National Air Pollution Control Programme:, Warsaw: MKiŚ, 2019.
[24] D Klimecka-Tatar, M Ingaldi, M Obrecht, "Sustainable developement in logistic – a strategy for management in terms of green transport", *Management Systems in Production Engineering*, 2021, Volume 29, Issue 2, pp. 91-96, DOI 10.2478/mspe-2021-0012
[25] Ulewicz, R., Siwiec, D., Pacana, A., Tutak, M., & Brodny, J., "Multi-Criteria Method for the Selection of Renewable Energy Sources in the Polish Industrial Sector", *Energies*, 2021, 14(9), 2386. https://doi.org/10.3390/en14092386
[26] Juda-Rezler, S., Reizer, M., & Maciejewska, P., "Assessment of air quality changes in Poland due to the implementation of the National Emission Ceilings Directive", *Atmospheric Environment,* 2017, 160, pp. 1-10.
[27] Rogula-Kozłowska, J., "Particulate matter in ambient air in Upper Silesia: sources, concentrations and health effects", *Environmental Monitoring and Assessment*, 185 (8), pp. 6939-6956, 2013.
[28] A. Bartosz and P. Oleniacz, "Local air quality management in Poland: challenges and perspectives", *Ecological Questions*, vol. 31, no. 1, pp. 27-36, 2020.
[29] https://www.iqair.com/poland/silesia/czestochowa with access data on 15.09. 2025.

Renata Stasiak-Betlejewska
ORCID ID: 0000-0001-8713-237X
Czestochowa University of Technology
Faculty of Management
Department of Production Engineering and Safety
Al. Armii Krajowej 19b 42-200 Czestochowa, Poland
e-mail: renata.stasiak-betlejewska@wz.pcz.pl