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GENERAL SOURCES OF POLLUTANTS

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INTRODUCTION

Air pollution is defined as contamination of the indoor or outdoor environment by chemical, physical or biological agents that alter the natural characteristics of the atmosphere. It represents a major environmental and public-health concern because exposure to polluted air is associated with respiratory and other diseases and contributes substantially to morbidity and mortality (WHO, 2026a). The problem is particularly important because pollutants originate from numerous sources and can transform after being released into the atmosphere.

Air pollutants originate from both natural physical and biological processes and human activities (Duffney et al., 2024; Saxena & Naik, 2019). Natural contributors include volcanic activity, forests, oceans, and other biological or physical processes, while anthropogenic sources include fossil-fuel combustion, transportation, power generation and industrial activities (Pénard-Morand & Annesi-Maesano, 2004). The identification and characterisation of these sources are important for understanding air-quality conditions and developing appropriate measures for emission reduction.

Air pollutants can also be distinguished according to whether they are emitted directly or formed subsequently in the atmosphere. Primary pollutants are released directly from a source, whereas secondary pollutants are generated through atmospheric chemical processes. Solar radiation and heat can contribute to the transformation of primary pollutants into secondary substances, including ozone and other photochemical pollutants (Kumar, 2010). Consequently, air

pollution is influenced not only by emission sources but also by atmospheric dispersion and transformation.

1. Classification of Air Pollution Sources

1.1 Natural sources

Natural sources can release both gases and particulate matter into the atmosphere. Naturally occurring particulate matter includes dust originating from the Earth's surface, sea salt and biological material such as pollen, spores, and plant and animal debris. Volcanic eruptions can produce particularly large quantities of gases and particles, while forest fires can generate substantial amounts of particulate matter (Pénard-Morand & Annesi-Maesano, 2004).

Other natural sources include lightning, which produces nitrogen oxides, and marine algae, which release hydrogen sulphide. Wetlands and other humid environments can emit methane, while wind erosion contributes particulate matter to the atmosphere. Natural processes can therefore influence air quality even in the absence of direct human activity (Kaur & Kumari, 2018).

Natural sources can sometimes produce very substantial emissions (e.g. the Etna volcano emits thousands of tonnes of sulphur dioxide during periods of activity). This illustrates the capacity of natural events to produce major short-term atmospheric pollution (Pénard-Morand & Annesi-Maesano, 2004).

1.2 Anthropogenic sources

Human activities constitute a major source of air pollution, particularly in urban environments. Anthropogenic sources can be divided into mobile sources, such as cars, trucks, aircraft and marine engines, and stationary or point sources, including factories and electric power plants (Pénard-Morand & Annesi-Maesano, 2004).

The principal anthropogenic source groups include industrial processes, residential heating, transportation, and agriculture. A substantial proportion of pollutants is directly associated with combustion processes in large power plants and piston engines, making emission reduction in these sectors an important element of air-pollution control (Kumar, 2010).

Human activities also influence the formation of secondary pollutants. Petroleum and chemical industries and transportation contribute to emissions of volatile organic compounds (VOC), while power stations and automobiles release nitrogen oxides. The increased presence of these precursor substances contributes to higher ozone concentrations and more frequent photochemical smog in densely populated and industrial regions (Mallik, 2018).

2. Major Anthropogenic Sources

2.1 Combustion and energy production

Combustion is one of the central processes associated with anthropogenic air pollution. The combustion of coal, fuel oil, wood, and natural gas is not complete and therefore produces pollutants such as carbon monoxide and hydrocarbons. High-temperature combustion also leads to the formation of nitrogen oxides (Pénard-Morand & Annesi-Maesano, 2004).

Fossil-fuel combustion is also important as it links air pollution with climate change. The same activities that generate many conventional air pollutants can also release greenhouse gases. Consequently, measures aimed at reducing fossil-fuel combustion can provide benefits for both air quality and climate mitigation (WHO, 2026a).

Large power plants and piston engines are described as major contributors to atmospheric pollution, meaning that controlling emissions from these sources is an important first step towards reducing pollutant concentrations (Kumar, 2010).

2.2 Transportation

Transportation is an important anthropogenic source, especially in urban areas. Road traffic has historically been identified as a major contributor to air pollution in large cities in industrialised countries. Vehicle combustion produces carbon monoxide and hydrocarbons, while high-temperature combustion contributes nitrogen oxide emissions (Pénard-Morand & Annesi-Maesano, 2004).

Transportation-related pollution includes more than road traffic: terrestrial, naval and aerial transportation are among the major anthropogenic source categories. This means that air-quality policies

need to consider different transport modes rather than focusing exclusively on passenger vehicles (Kumar, 2010).
The WHO identifies cleaner transport as one of the important areas for reducing outdoor air pollution. Suggested approaches include rapid urban transit, walking and cycling networks, rail transport, lower-emission vehicles and fuels, and fuels with reduced sulphur content (WHO, 2024).

2.3 Industrial processes

Industry contributes to air pollution through both combustion and specific production processes. Industrial activities can release pollutants that are characteristic of specific materials and processes (e.g. fluorine derivatives and aluminium) (Pénard-Morand & Annesi-Maesano, 2004).
The treatment of ores can release heavy metals, including cadmium, zinc, and lead. Waste incineration can also be a source of mercury. Industrial emissions are therefore not restricted to the major conventional pollutants but may include substances with specific toxicological characteristics (Mallik, 2018).
Industrial emission reduction is therefore dependent on the process involved. The WHO identifies cleaner technologies that reduce industrial smokestack emissions as one possible approach to lowering air pollution. Industrial pollution control consequently combines technological measures with appropriate regulatory requirements (WHO, 2024).

2.4 Residential energy and household air pollution

Residential energy use represents an important source of household air pollution. Around 2.1 billion people worldwide still cook using open fires or inefficient stoves fuelled by kerosene, biomass, coal, and other solid fuels. Such combustion generates harmful pollutants, including fine particulate matter (WHO, 2025).
The health consequences of household air pollution are particularly important in poorly ventilated dwellings. Indoor smoke can result in very high concentrations of fine particles, therefore women and

children experience particularly high exposure because they commonly spend more time near domestic cooking fires (WHO, 2025). Household air pollution is also relevant to outdoor air quality. Inefficient stove combustion produces pollutants such as black carbon and methane, while emissions from household energy use can contribute to ambient pollution. The transition towards cleaner household fuels and technologies is therefore relevant to both indoor and outdoor environmental health (IEA et al., 2025; WHO, 2025).

2.5 Agriculture

Agricultural systems constitute another important source of atmospheric emissions. The use of nitrogen fertilisers generates nitrous oxide and ammonia. Ammonia participates in atmospheric processes associated with acidification, while methane is produced in connection with livestock digestion and the handling of animal waste (Pénard-Morand & Annesi-Maesano, 2004).

Agricultural emissions therefore include both air pollutants and greenhouse gases. The relationship between agriculture and atmospheric pollution illustrates the importance of considering different environmental effects together when developing emission-reduction strategies (Goswami & Chandra, 2018).

2.6 Waste management

Waste-related activities can also contribute to air pollution. Domestic garbage incineration is a source of mercury, while agricultural and municipal waste management are areas in which changes in practice can reduce emissions (Pénard-Morand & Annesi-Maesano, 2004).

WHO identifies waste reduction, separation, recycling, reuse, and improved biological waste treatment as feasible approaches. Anaerobic digestion can be used to produce biogas, while where incineration is unavoidable, strict emission controls are essential (WHO, 2024).

3. Major Air Pollutants

3.1 Particulate matter

Particulate matter (PM) is one of the principal indicators used in air-quality assessment. PM includes a mixture of substances such as sulphates, nitrates, ammonia, sodium chloride, black carbon, mineral dust, and water. Fine particles are particularly important from a health perspective because exposure is strongly associated with adverse health effects (WHO, 2024).

PM_{10} and $PM_{2.5}$ are distinguished according to particle size: PM_{10} consists of particles with a diameter of 10 µm or less, while $PM_{2.5}$ consists of particles measuring 2.5 µm or less. These particles can originate from both natural processes and anthropogenic combustion sources (Pénard-Morand & Annesi-Maesano, 2004).

In Europe, particulate matter remains one of the pollutants for which additional reductions are required. The EEA's 2026 assessment reports that more than 30% of the monitoring stations considered in its 2024 benchmarking recorded particulate-matter concentrations above the revised standards intended for 2030 (EEA, 2025b, 2026).

3.2 Nitrogen oxides and nitrogen dioxide

Nitrogen oxides are strongly associated with combustion. Nitrogen dioxide (NO_2) is commonly released through fuel combustion in the transportation and industrial sectors, while nitrogen oxides (NO_X) can also originate from power generation and other combustion processes (WHO, 2024).

NOx are important not only as directly emitted pollutants but also because they participate in atmospheric reactions. Together with VOCs and sunlight, they contribute to the formation of ground-level ozone, linking combustion emissions to secondary photochemical pollution (Pénard-Morand & Annesi-Maesano, 2004).

The European monitoring data show that NO_2 remains a relevant air-quality issue, although its concentrations are already below certain revised 2030 standards at most monitoring stations. Nevertheless, the 2025 data indicate that NO_2 guideline exceedances remained widespread when compared with WHO recommendations (Targa et al., 2026b).

3.3 Sulphur dioxide

Sulphur dioxide (SO_2) is associated mainly with the combustion of sulphur-containing fossil fuels and the smelting of mineral ores containing sulphur. Coal and oil are therefore important sources of this pollutant (WHO, 2024).

SO_2 has historically been one of the major gaseous air pollutants. In Europe, concentrations have declined considerably, and the EEA reports that only a limited number of monitoring stations recorded concentrations above current EU standards for SO_2 (EEA, 2026).

3.4 Carbon monoxide

Carbon monoxide (CO) is a colourless, odourless and toxic gas generated by incomplete combustion of carbonaceous fuels, which include wood, petrol, charcoal, natural gas, and kerosene (WHO, 2024).

Incomplete combustion is particularly relevant to household air pollution, where inefficient stoves and polluting fuels can generate substantial quantities of CO and particulate matter. Improving household energy technologies is therefore an important means of reducing exposure to combustion-related pollutants (WHO, 2025).

3.5 Ozone and volatile organic compounds

Ground-level ozone (O_3) is one of the major components of photochemical smog. Unlike primary pollutants such as carbon monoxide emitted directly from combustion, ozone is formed in the atmosphere through reactions involving precursor gases in the presence of sunlight (WHO, 2024).

Anthropogenic emissions of VOCs and NO_x increase the potential for ozone formation. Petroleum and chemical industries and transportation contribute VOCs, while automobiles and power stations contribute NO_x. These emissions can result in increased ozone concentrations, particularly in densely populated and industrialised regions (Pénard-Morand & Annesi-Maesano, 2004).

3.6 Toxic metals

Toxic metals constitute another group of pollutants considered in European air-quality monitoring, which include lead, arsenic, cadmium, nickel and mercury (Pénard-Morand & Annesi-Maesano, 2004).

The EEA's 2024 assessment found that exceedances of European standards were reported at five stations for arsenic, at one station for lead and at four stations for nickel, while no exceedances were reported for cadmium. These results illustrate that the occurrence of individual pollutants can vary considerably between monitoring locations (Targa et al., 2026a).

4. Health and Environmental Effects

Air pollution is associated with a broad range of adverse health effects. Exposure to outdoor air pollution contributes to cardiovascular and respiratory diseases and cancers, while fine particulate matter is particularly important in relation to these outcomes (WHO, 2024).

The health burden is not distributed equally across populations. Children, older people, and individuals with certain medical conditions are among the groups that are particularly vulnerable to pollution-related health effects. This makes air-quality improvement an important component of preventive public-health policy (EC, 2026).

The global burden of ambient air pollution is substantial. WHO estimates that outdoor air pollution caused approximately 4.2 million premature deaths worldwide in 2019, with cardiovascular and respiratory diseases and cancers among the associated causes. Approximately 89% of these premature deaths occurred in low- and middle-income countries (WHO, 2024).

Household air pollution represents an additional health burden. It was responsible for an estimated 2.9 million deaths in 2021, including more than 309,000 deaths among children under five. Associated diseases include ischaemic heart disease, stroke, lower respiratory infections, COPD, and lung cancer (WHO, 2025).

The environmental effects of pollution are also significant. Pollution is identified by the European Commission as one of the main causes of biodiversity loss and as a factor reducing the capacity of ecosystems to

provide services such as carbon sequestration and decontamination (EC, 2026).

Air pollution is closely connected with climate change because many of its drivers, particularly fossil-fuel combustion, are also sources of greenhouse gases (Thurston, 2025). Measures that reduce air pollution can therefore simultaneously reduce the health burden and contribute to climate-change mitigation (WHO, 2026a).

5. Air Quality in Europe

European air quality has improved over the last two decades, largely because of European, national, and local legislation designed to reduce emissions. Nevertheless, air pollution remains Europe's greatest environmental health risk, and important exceedances continue to occur for several pollutants (EEA, 2026).

The EEA assessment of 2024 data reports that more than 12% of reporting stations exceeded the current EU standards for PM_{10}, ozone and benzo(a)pyrene. When the measurements are compared with WHO air-quality guidelines, the situation is considerably more demanding, particularly for $PM_{2.5}$ and ozone (EEA, 2026).

The 2025 European data provide additional evidence that substantial differences remain between current air quality and WHO guideline levels. The WHO guideline for $PM_{2.5}$ was exceeded at 94% of monitoring stations and the guideline for ozone at 98% of stations in the preliminary 2025 assessment (Targa et al., 2026b).

European air-quality policy has consequently been strengthened. Directive (EU) 2024/2881 entered into force on 10 December 2024 and introduced revised standards intended to be achieved by 2030. The revised framework brings EU standards closer to WHO recommendations and updates standards for 12 air pollutants: $PM_{2.5}$ and PM_{10}, ozone, nitrogen dioxide and nitrogen oxides, sulphur dioxide, benzene, lead, carbon monoxide, arsenic, cadmium, nickel and benzo(a)pyrene (EC, 2024).

The EEA's comparison of existing concentrations with the revised 2030 standards should be interpreted as a distance-to-target assessment rather than as a formal future compliance assessment. It is based on available monitoring stations and does not incorporate projected

future emissions or possible changes to monitoring networks (EEA, 2026).

6. Monitoring and Identification of Pollution Sources

Because atmospheric pollution originates from multiple sources, identifying the contribution of individual sources is an important part of air-quality analysis. Different source types emit characteristic combinations of chemical elements, and these characteristics can be used to estimate their relative contributions to pollution measured at a particular location (Friedlander, 1973).

European monitoring systems include a defined group of pollutants that serve as indicators of important pollution problems: SO_2, NOx, PM_{10}, $PM_{2.5}$, ozone, CO, VOCs and several toxic metals. They are monitored because they are associated with various pollution sources and are known or suspected to have harmful effects on health or the environment (Pénard-Morand & Annesi-Maesano, 2004).

The WHO Ambient Air Quality Database provides measurements of annual mean concentrations for NO_2, PM_{10} and $PM_{2.5}$. The database is designed to represent average conditions for cities and towns rather than individual monitoring stations and incorporates official national and subnational datasets and other official sources. The database also has some important limitations. Differences in monitoring coverage, accessibility, measurement techniques, data quality, and spatial and temporal coverage restrict direct comparisons between locations. For this reason, WHO explicitly states that the database should not be used to rank cities or make straightforward comparisons between countries (WHO, 2026b).

7. Pollution Control and Policy Responses

Information on past pollution level trends is available via the EEA's online air quality statistics data viewer (EEA, 2025a), which shows yearly data for all 12 air pollutants with legal limits under EU air quality laws.

Reducing air pollution requires action across several sectors as many sources are beyond the control of individuals. Policy responses

therefore need to involve areas such as energy, transport, waste management, urban planning, agriculture, and industry (WHO, 2024). For transportation, proposed measures include rapid urban transit, walking and cycling networks, rail transport, cleaner heavy-duty vehicles, and lower-emission fuels. In power generation, increased use of renewable, combustion-free sources such as solar, wind, and hydropower are identified as one approach to reducing emissions (WHO, 2024).

Waste management can also be improved through waste reduction, separation, recycling, reuse, and biological treatment. Anaerobic digestion can provide an alternative approach to open incineration by producing biogas, while unavoidable incineration requires strict emission controls (WHO, 2024).

For households, WHO recommends expanding access to cleaner fuels and technologies. These include solar energy, electricity, biogas, LPG, natural gas, alcohol fuels, and biomass stoves that meet the emission targets established in WHO guidance (WHO, 2025).

Financial support, improved ventilation and housing design, and communication campaigns are identified as possible measures for accelerating the transition to cleaner household energy. Such interventions are particularly important because many people continue to rely on polluting fuels and technologies (WHO, 2025).

Regulatory action is another important component. European legislation establishes legally binding limit values as well as target values for pollutants. A limit value is legally binding once applicable, whereas a target value involves an obligation to take the necessary measures without disproportionate costs to achieve the specified objective (EC, 2025).

8. Zero Pollution and Integrated Environmental Policy

The European Union's Zero Pollution Action Plan places air pollution within a wider framework addressing pollution of air, water, and soil. The long-term objective is to reduce pollution to levels that are no longer considered harmful to human health and natural ecosystems (EC, 2026).

The Action Plan establishes several 2030 objectives, including a 55% reduction in premature deaths caused by air pollution and a 25% reduction in the EU ecosystems where air pollution threatens biodiversity. The plan also aims to strengthen pollution prevention, implementation of environmental legislation, and the identification of remaining policy gaps (Singh & Kumar, 2018).
The 2026 Mid-Term Review of the Action Plan builds on the scientific evidence presented in the 2025 Zero Pollution Monitoring and Outlook. It identifies governance and implementation, investment, integration, innovation and international cooperation as important enabling factors for achieving the established objectives (EC, 2026).

CONCLUSION

Air pollution has multiple natural and anthropogenic origins. Natural processes such as volcanic eruptions, forest fires, wind erosion, and biological activity can make substantial contributions, while human activities are particularly important in urban and industrial environments (Pénard-Morand & Annesi-Maesano, 2004).
Among anthropogenic sources, combustion, transportation, industrial processes, residential energy use, agriculture, and waste management are particularly important. These sources emit both primary pollutants and precursor substances that can subsequently participate in atmospheric reactions (Kumar, 2010).
The main pollutants include particulate matter, nitrogen oxides, sulphur dioxide, carbon monoxide, ozone, volatile organic compounds and toxic metals. Their concentrations and impacts depend on emission sources, atmospheric processes, and local conditions (WHO, 2024).
Air pollution remains a substantial health and environmental problem despite improvements in Europe. The EEA data demonstrate progress for several pollutants but also show that important challenges remain, particularly for particulate matter and ozone and in relation to the stricter WHO air quality guideline (AQG) levels (WHO, 2021).
An integrated approach to pollution reduction is essential. Cleaner household energy, lower-emission transport, improved industrial technologies, cleaner power generation, improved waste

management, and coordinated environmental policy can contribute to reducing exposure and associated health and environmental effects (WHO, 2024).

The European regulatory framework demonstrates the importance of combining monitoring, legally defined standards, and measures directed at emission sources. The revised 2030 standards and the Zero Pollution Action Plan represent further steps towards reducing pollution and bringing European air quality closer to health-based objectives (EC, 2024, 2026).

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