
ATMOSPHERIC AIR: GLOBAL TRENDS, MONITORING, AND CLIMATE CHALLENGES

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INTRODUCTION

Atmospheric air is one of the most important components of the natural environment, and its condition directly affects public health, the functioning of natural ecosystems, and the prospects for sustainable socio-economic development. The atmosphere facilitates gas exchange among the components of the biosphere, contributes to climate formation, participates in the cycling of matter and energy, and helps maintain ecological balance. At the same time, the intensive development of industry, energy, transport, agriculture, and urbanization processes has led to a significant increase in anthropogenic pressure on the atmosphere, making air pollution a global environmental problem.

The main anthropogenic sources of atmospheric air pollution continue to include industrial and energy facilities, road transport, heating systems, fossil fuel and biomass combustion, agricultural production, and waste management. A wide range of pollutants is released into the atmosphere, among which particulate matter (PM_{2.5} and PM₁₀), nitrogen and sulfur oxides, carbon monoxide, volatile organic compounds, heavy metals, black carbon, and other components are of particular concern. Their accumulation adversely affects human health, the condition of natural ecosystems, and the dynamics of climate processes.

A distinctive feature of contemporary atmospheric pollution is its transboundary nature. The movement of air masses facilitates the transport of gaseous pollutants and aerosols over considerable distances from their sources. As a result, industrial emissions, smoke from wildfires, dust, and other pollutants can affect air quality far beyond the boundaries of individual regions and countries. This highlights the need to strengthen international cooperation, improve monitoring systems, and ensure the timely exchange of environmental information.

The issue of atmospheric air quality is closely linked to global climate change. On the one hand, certain atmospheric pollutants affect the Earth's radiation balance and the climate system; on the other hand, rising air temperatures, the increasing frequency of droughts, heat waves, and large-scale wildfires alter

the conditions governing the formation, transformation, and dispersion of pollutants. Therefore, atmospheric air protection and climate policy should be regarded as interconnected areas of environmental security.

These issues are particularly relevant to Ukraine. The full-scale war has significantly transformed the structure of anthropogenic pressure on atmospheric air. The destruction of industrial and energy facilities, fires, explosions, damage to infrastructure, changes in transport flows, the relocation of enterprises, and the widespread use of autonomous energy supply systems are creating new environmental risks. At the same time, hostilities complicate systematic observations and the collection of complete and reliable information on atmospheric air quality throughout the country. Under these conditions, the modernization of the national environmental monitoring system is becoming particularly important.

Modern atmospheric air monitoring is gradually evolving from a traditional network of stationary monitoring stations into an integrated digital system. Satellite observations and European information systems play an important role in this transformation, expanding the possibilities for spatial analysis of atmospheric conditions and forecasting the dispersion of pollutants.

For Ukraine, the modernization of the monitoring system is also of particular importance in the context of European integration and post-war recovery. Harmonization of national environmental policy with the approaches adopted by the European Union requires the improvement of air quality assessment methods, enhanced reliability and accessibility of data, automation of data transmission, and open public access to environmental information. At the same time, the reconstruction of the country's industrial and energy potential provides an opportunity to introduce modern low-carbon technologies and advanced emission control systems.

The aim of the study is to provide a comprehensive synthesis of contemporary scientific approaches to assessing the state of atmospheric air, to analyze global and national trends in air pollution, to examine modern monitoring systems, and to identify the interrelationships between air quality, anthropogenic pressure, and climate change.

The practical significance of the study lies in the potential application of its findings to improve the atmospheric air monitoring system in Ukraine, substantiate environmental protection measures, develop digital monitoring infrastructure, and enhance the effectiveness of environmental management decisions. The comprehensive integration of traditional observation methods with satellite-based, sensor, geoinformation, and intelligent technologies should become one of the key directions in developing a modern environmental security system in Ukraine and ensuring its sustainable post-war development.

1. Contemporary Sources and Chemical Mechanisms of Technogenic Atmospheric Air Pollution

In recent years, the international scientific community has increasingly regarded atmospheric air as a key link in the interactions among natural ecosystems, public health, and socio-economic development. Within these conceptual frameworks, atmospheric air quality is no longer viewed exclusively as an environmental characteristic but has become one of the fundamental indicators of sustainable development, environmental security, and the quality of life of the population. This approach makes it possible to assess atmospheric processes not in isolation but as an integral component of the complex functioning of natural and anthropogenic systems.

At the same time, the rapid increase in technogenic pressure significantly exceeds the capacity of the atmosphere's natural self-purification mechanisms. While natural processes are capable of maintaining a relative equilibrium in atmospheric gas composition under conditions of moderate pollutant inputs, the current scale of industrial emissions, transport-related emissions, fossil fuel combustion, and urbanization processes increasingly exceeds the assimilative capacity of the atmospheric system. This is reflected in the increasing frequency of episodes of severe air pollution, the prolonged duration of smog events, the intensification of transboundary pollutant transport, and the emergence of new environmental risks to human populations and natural ecosystems.

Under current conditions, the impact of military activities on atmospheric air quality also deserves particular attention. The destruction of industrial enterprises, oil depots, energy facilities, transport infrastructure, and residential buildings is accompanied by the release of a wide range of toxic substances into the atmosphere, including nitrogen oxides, sulfur oxides, fine particulate matter, polycyclic aromatic hydrocarbons, dioxins, heavy metals, and other hazardous compounds. For Ukraine, this problem is not only of environmental but also of strategic importance, as the consequences of wartime atmospheric pollution may persist for a considerable period, affecting public health, ecosystem productivity, and post-war territorial recovery processes.

Thus, atmospheric air constitutes an extremely complex, multi-level system whose functioning is determined by the interaction of natural and anthropogenic processes. Increasing technogenic pressure, the intensification of photochemical transformations, ongoing global climate change, and the growing transboundary transport of pollutants necessitate a transition from the traditional monitoring of individual pollutant concentrations to integrated air quality management. This approach forms the methodological basis of contemporary environmental policy, international monitoring systems, and further research into the sources and chemical characteristics of technogenic atmospheric pollution.

The current stage of civilization development is characterized by an unprecedented increase in anthropogenic pressure on atmospheric air, which is a natural consequence of industrialization, urbanization, the intensification of transport flows, economic globalization, and growing global demand for energy resources. Over the past half-century, the scale and structure of technogenic emissions have undergone substantial transformations in both quantitative and qualitative terms. Whereas in the mid-twentieth century large industrial enterprises were the predominant sources of atmospheric pollution, today a complex, multicomponent emission system has emerged in which transport, energy production, the agro-industrial sector, housing and municipal services, construction, extractive industries, and other types of economic activity play significant roles.

Recent studies indicate that the structure of anthropogenic sources of atmospheric air pollution is constantly changing under the influence of technological development, national environmental policies, the transition towards a low-carbon economy, and global socio-economic transformations. In the European Union, emissions of sulfur dioxide and heavy metals have decreased substantially over recent decades due to the modernization of the energy sector, the implementation of best available techniques, stringent environmental legislation, and the development of renewable energy sources. At the same time, so-called diffuse sources of pollution are becoming increasingly important. These comprise millions of relatively small individual sources, including motor vehicles, private heating systems, small enterprises, construction sites, and agricultural holdings. The cumulative impact of such sources often exceeds the contribution of individual large industrial facilities, consi

The Energy Sector as a Dominant Source of Technogenic Atmospheric Pollution

Despite the rapid development of renewable energy, the energy sector remains one of the largest anthropogenic sources of atmospheric air pollution worldwide. The generation of electricity and heat from fossil fuels is accompanied by substantial emissions of carbon dioxide, sulfur oxides, nitrogen oxides, carbon monoxide, particulate matter, volatile organic compounds, and heavy metals. The magnitude of these emissions depends on the type of fuel used, the technological level of the equipment, the efficiency of flue-gas treatment systems, and the environmental standards in force in a particular country.

Hard coal and lignite remain among the most environmentally hazardous types of fuel.

Significant changes in the structure of energy-related emissions have occurred as a result of the development of renewable energy. The large-scale deployment of solar and wind power plants, along with the increasing share of hydropower and bioenergy, contributes to reducing the consumption of

fossil fuels. Particular attention should be paid to bioenergy, which is often regarded as a climate-neutral energy source. However, biomass combustion may be accompanied by substantial emissions of fine particulate matter, carbon monoxide, organic aerosols, and polycyclic aromatic hydrocarbons. Therefore, the environmental performance of bioenergy technologies largely depends on the type of biofuel used, combustion conditions, and the efficiency of flue-gas treatment systems¹.

Thus, the energy sector remains a key factor influencing the chemical composition of atmospheric air on a global scale. Further reduction of its adverse environmental impact requires comprehensive modernization of energy infrastructure, the development of zero-carbon technologies, improvements in energy efficiency, and the widespread implementation of industrial emission control and treatment systems. At the same time, assessments of the environmental safety of the energy sector should take into account not only direct atmospheric emissions but also the entire life cycle of energy technologies, in accordance with contemporary principles of sustainable development and the circular economy.

Industry as a Complex Source of Technogenic Atmospheric Air Pollution

The industrial sector has traditionally been one of the most significant sources of anthropogenic pressure on atmospheric air. Despite the substantial modernization of production processes in most economically developed countries, industry continues to account for a considerable share of global emissions of gaseous and particulate pollutants. Industrial emissions are characterized by their high concentrations, diverse chemical composition, and capacity to form complex multicomponent mixtures that undergo intensive physicochemical transformations after being released into the atmosphere.

Unlike the transport or residential sectors, where fuel combustion products predominate, industrial enterprises generate a wide range of specific substances whose composition is determined by production technology, the type of raw materials used, operating conditions of the equipment, and the level of environmental modernization. Consequently, industry is a source not only of conventional air pollutants, such as nitrogen oxides, sulfur oxides, carbon monoxide, and particulate matter, but also of numerous toxic trace components, including heavy metals, polycyclic aromatic hydrocarbons, dioxins, furans, benzene, formaldehyde, persistent organic pollutants, and other hazardous substances.

Large industrial agglomerations, where metallurgical enterprises, thermal power plants, cement plants, chemical facilities, and oil refineries operate simultaneously, pose a particular environmental hazard.

¹ Боголюбов В. М., Клименко М. О., Мокін В. Б. та ін. Моніторинг довкілля : підручник. Херсон : Грінь Д. С., 2011. 530 с.

The metallurgical industry is among the most resource-intensive and environmentally hazardous industrial sectors. Virtually all technological stages involved in the production of ferrous and non-ferrous metals are accompanied by atmospheric emissions of varying composition and intensity. Sinter production, coke-chemical processes, blast-furnace smelting, basic oxygen steelmaking, electric steelmaking, and rolling processes generate a specific spectrum of pollutants dominated by nitrogen oxides, sulfur oxides, carbon monoxide, particulate matter, heavy metals, and organic toxicants.

Particular attention should be paid to particulate emissions from metallurgical enterprises. Unlike natural dust, metallurgical aerosols contain significant concentrations of iron, manganese, zinc, cadmium, chromium, nickel, lead, and other metals characterized by high biological activity.

Chemical industry enterprises represent one of the most complex sources of atmospheric pollution, as they handle a wide range of organic and inorganic substances. A distinctive feature of this sector is the considerable diversity of technological processes, which results in a complex and variable composition of atmospheric emissions.

The principal pollutants include volatile organic compounds (VOCs), ammonia, chlorine, hydrogen fluoride, hydrogen sulfide, formaldehyde, benzene, toluene, xylene, phenols, and other toxic substances. A significant proportion of these compounds act as precursors of photochemical smog and secondary organic aerosols. Once released into the atmosphere, they actively interact with nitrogen oxides under the influence of solar radiation, contributing to the formation of ground-level ozone, one of the most hazardous secondary pollutants in the modern atmosphere. Accidental releases from chemical industry facilities pose a particularly serious environmental hazard.

Cement production is one of the most energy-intensive industrial processes and, at the same time, an important source of atmospheric emissions. Cement plants generate large amounts of carbon dioxide, particulate matter, nitrogen oxides, sulfur dioxide, and fine particles of mineral origin.

Oil refineries generate a specific spectrum of atmospheric pollutants, including hydrogen sulfide, volatile organic compounds, benzene, polycyclic aromatic hydrocarbons, nitrogen oxides, and sulfur dioxide. A significant proportion of these emissions is associated not only with technological processes but also with the evaporation of crude oil and petroleum products during transportation and storage.

The Transport Sector as a Dynamic Source of Atmospheric Air Pollution

At the beginning of the twenty-first century, the transport sector emerged as one of the most dynamic factors influencing atmospheric air quality. The rapid growth in motor vehicle use, the globalization of international trade, the expansion of air transportation, and the intensification of logistics flows have substantially altered

the structure of atmospheric emissions. Whereas during the second half of the twentieth century large stationary industrial facilities were the primary contributors to atmospheric pollution, mobile emission sources are now playing an increasingly important role, with their number continuing to grow worldwide each year.

A distinctive feature of transport-related pollution is its spatial concentration directly within populated areas. Unlike industrial enterprises, which are often located outside residential zones, transport infrastructure passes through densely populated urban areas, resulting in continuous exposure to air pollutants within the human breathing zone.

The main components of transport emissions include nitrogen oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), volatile organic compounds (VOCs), fine particulate matter ($\text{PM}_{2.5}$ and PM_{10}), black carbon, polycyclic aromatic hydrocarbons, aldehydes, and numerous ultrafine particles. Their relative proportions depend on the type of vehicle, engine technology, fuel quality, operating conditions, and the level of vehicle maintenance.

Contemporary research pays particular attention to non-exhaust emissions, whose contribution to air pollution has long been underestimated. These include particles generated by the wear of tires, brake pads, and road surfaces, as well as the resuspension of road dust by air currents. In large cities, such sources may account for a significant proportion of the total PM_{10} mass. With the increasing adoption of electric vehicles, their relative importance is expected to grow further, since the absence of exhaust emissions does not eliminate the mechanical generation of particulate matter.

Road transport is a major source of nitrogen oxide emissions in urban ecosystems. In the presence of solar radiation, these compounds actively participate in photochemical reactions leading to the formation of ground-level ozone and secondary organic aerosols. Thus, transport not only directly deteriorates atmospheric air quality but also triggers the formation of secondary pollution, the magnitude of which often exceeds the impact of primary emissions².

Diesel-powered transport remains a significant environmental challenge.

A distinct area of contemporary research focuses on the impact of transport electrification on atmospheric air quality. The large-scale adoption of electric vehicles undoubtedly contributes to reducing local emissions of nitrogen oxides, carbon monoxide, and volatile organic compounds. At the same time, assessing the environmental performance of electric transport requires consideration of its entire life cycle, including battery production, electricity generation, and the disposal or recycling of components at the end of their service life.

² Защепкіна Н., Рудницький Р. Аналіз основних чинників, які впливають на рівень забруднення атмосферного повітря. *Вимірювальна та обчислювальна техніка в технологічних процесах*. 2026. № 1. С. 21–27. URL: <https://doi.org/10.31891/2219-9365-2026-85-3>.

Table 1

Comparative Characteristics of Major Anthropogenic Sources of Air Pollution, Their Chemical Composition, and Environmental Impacts^{3, 4, 5, 6}

Pollution Source	Key Pollutants	Emissions Formation Features	Impact Scale	Major Environmental Impacts	Priority Environmental Measures
Thermal power engineering	CO ₂ , SO ₂ , NO _x , PM _{2.5} , PM ₁₀ , CO, Hg	Combustion of hard coal, lignite, fuel oil, and natural gas	Global, regional	Acid precipitation, smog, climate change, ecosystem degradation	Transition to RES, BAT, electrostatic precipitators, desulfurization, carbon capture and storage (CCUS)
Metallurgy	PM _{2.5} , PM ₁₀ , Fe, Mn, Zn, Pb, Cd, SO ₂ , NO _x , CO	Coking, sintering, blast furnace, and steelmaking operations	Local, regional	Air and soil pollution, accumulation of heavy metals, carcinogenic risk	Gas cleaning plants, sealing of technological processes, closed-loop production cycles
Chemical industry	VOC, NH ₃ , Cl ₂ , H ₂ S, HF, formaldehyde, benzene, toluene	Chemical synthesis, production of fertilizers, polymers, and acids	Local	Photochemical smog, toxic effects, formation of secondary aerosols	LDAR, catalysts, equipment sealing, automated monitoring
Cement industry	CO ₂ , PM ₁₀ , PM _{2.5} , NO _x , SO ₂	Clinker burning, raw material grinding, material transportation	Local, regional	Dust pollution, contribution to global CO ₂ emissions	Bag filters, alternative fuels, low-carbon cements, CCUS
Oil refining industry	VOC, benzene, PAHs, SO ₂ , H ₂ S, NO _x	Oil processing, storage, and transportation of petroleum products	Regional	Ozone formation, carcinogenic impact, toxic air pollution	LDAR systems, storage tank sealing, vapor recovery units

³ World Health Organization. WHO Global Air Quality Guidelines: Particulate Matter (PM_{2.5} and PM₁₀), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. Geneva : WHO, 2021. 290 p.

⁴ IPCC. *Climate Change 2023: Synthesis Report*. Geneva, 2023.

⁵ European Environment Agency. Air Quality Status Report 2025. Luxembourg : Publications Office of the European Union, 2025.

⁶ European Commission. Zero Pollution Action Plan: Towards Zero Pollution for Air, Water and Soil. Brussels : European Commission, 2021.

Table 1 (Continued)

Pollution Source	Key Pollutants	Emissions Formation Features	Impact Scale	Major Environmental Impacts	Priority Environmental Measures
Road transport	NO _x , CO, CO ₂ , VOC, PM _{2.5} , black carbon	Operation of internal combustion engines, wear of tires and road surface	Local, global	Urban smog, noise pollution, respiratory diseases	Electric vehicles, catalytic converters, Euro standards, public transport development
Aviation transport	CO ₂ , NO _x , water vapor, ultrafine particles	Operation of aircraft engines at high altitudes	Global	Intensification of the greenhouse effect, contrail formation	SAF fuels, route optimization, new engine designs
Maritime transport	SO ₂ , NO _x , PM, CO ₂	Use of heavy fuel oil	Global	Coastal area pollution, acid rain	Low-sulfur fuels, LNG, port electrification
Agriculture	NH ₃ , CH ₄ , N ₂ O, PM	Livestock farming, fertilizer application, soil tillage	Regional	Secondary fine particulate matter, eutrophication, climate change	Precision agriculture, fertilizer application optimization, biogas plants
Housing and communal sector	PM _{2.5} , CO, NO _x , SO ₂ , benzo(a)pyrene	Residential heating, combustion of solid fuels and waste	Local	Cold-season smog, increased risk of respiratory diseases	Building energy efficiency, district heating, ban on waste burning
Construction sector	PM ₁₀ , PM _{2.5} , SiO ₂ , cement dust	Demolition, earthworks, material transportation	Local	Dust accumulation in areas, deterioration of urban air quality	Construction site watering/irrigation, dust control screens, modern construction techniques
Mining industry	PM, CH ₄ , SO ₂ , NO _x	Open-pit quarries, underground mines, blasting operations	Local, regional	Dust load, landscape degradation, methane emissions	Dust suppression, mine degasification, land reclamation
Military activities	PM _{2.5} , PM ₁₀ , CO, NO _x , SO ₂ , PAHs, dioxins, heavy metals	Fires, explosions, destruction of industrial facilities, combustion of fuels and lubricants	Local, regional, transboundary	Complex toxic air pollution, transboundary transport of aerosols, long-term public health impacts	Operational monitoring systems, satellite surveillance, post-war environmental reclamation

Aviation and maritime transport are equally important, as they support the functioning of the global economy while simultaneously creating specific environmental challenges. Aviation is a source of nitrogen oxides, water vapour, soot, and aerosol emissions in the upper troposphere, affecting the formation of condensation trails (contrails) and altering the atmospheric radiation balance. Maritime transport, particularly vessels using heavy fuel oils, remains a significant source of sulfur dioxide, nitrogen oxides, and fine particulate matter. In response to these challenges, the International Maritime Organization (IMO) has introduced stricter requirements for the sulfur content of marine fuels, which have already demonstrated positive effects in reducing atmospheric emissions in coastal regions.

In the future, the key directions for improving the environmental sustainability of the transport sector include the development of public transport, electrification of the vehicle fleet, the adoption of hydrogen technologies, improvements in urban mobility, digital management of traffic flows, and the integration of transport policy with Smart City concepts. At the same time, achieving a substantial environmental effect will only be possible through a comprehensive approach combining technological innovation, environmental regulation, and changes in the transport behaviour of the population.

Agriculture as a Specific Source of Atmospheric Pollution

For a long time, the agricultural sector was regarded primarily as an economic activity with a relatively minor impact on atmospheric air quality. However, contemporary research indicates that the intensification of agricultural production has substantially altered the nature of interactions between agroecosystems and the atmosphere. According to estimates by international environmental organizations, agriculture is currently one of the leading anthropogenic sources of ammonia (NH_3), methane (CH_4), nitrous oxide (N_2O), as well as secondary fine particulate matter formed through atmospheric chemical reactions.

A distinctive feature of agricultural emissions is that most of them are diffuse in nature, which significantly complicates their monitoring, quantitative assessment, and regulation. For this reason, the agricultural sector is increasingly regarded as one of the most challenging areas of contemporary environmental policy.

Livestock farming makes the largest contribution to agricultural air pollution. The raising of cattle, pigs, and poultry is accompanied by intensive emissions of ammonia, methane, hydrogen sulfide, and other gaseous compounds.

Another important factor is the application of mineral fertilizers. Improper fertilizer application practices, excessive use of nitrogen compounds, and adverse weather conditions lead to intensive ammonia volatilization and the formation of nitrous oxide, one of the most potent greenhouse gases. In addition

to their direct impact on atmospheric air quality, these processes contribute to global climate change, further emphasizing the inseparable relationship between air quality and the Earth's climate system⁷.

An additional source of atmospheric pollution is the mechanical cultivation of soils. During ploughing, cultivation, harvesting, and the transportation of agricultural products, considerable amounts of mineral dust are released into the atmosphere. Under arid climatic conditions or where soil degradation occurs, the scale of such dust emissions may increase substantially. Dust originating from degraded arable land poses a particular hazard, as it often contains residues of agrochemicals, heavy metals, and microorganisms.

The contemporary concept of sustainable agriculture involves a gradual transition towards precision farming technologies, digital management of fertilizer application, the use of biogas facilities, improvements in organic waste management systems, and optimization of land-use patterns. Taken together, these measures can significantly reduce atmospheric emissions without compromising agricultural productivity.

The Residential and Municipal Sector and the Urban Environment

The residential and municipal sector occupies a significant place in the contemporary structure of anthropogenic emissions, with its impact being particularly pronounced in densely populated urban agglomerations. Unlike industry, where pollution is generated by a limited number of large enterprises, the residential and municipal sector comprises numerous small emission sources that collectively exert considerable technogenic pressure on atmospheric air.

The main sources of pollution include individual heating systems, boiler plants, solid fuel combustion, the use of generators, cooking, household waste burning, and construction activities. In many Central and Eastern European countries, residential heating with wood and coal remains one of the major sources of winter smog.

Uncontrolled burning of household waste poses a particular environmental hazard. The combustion of polymeric materials, rubber, paints and coatings, and other synthetic components results in the formation of dioxins, furans, polycyclic aromatic hydrocarbons, chlorinated organic compounds, and heavy metals. Most of these substances are characterized by high toxicity, resistance to biodegradation, and the ability to bioaccumulate.

In modern cities, construction activities represent an additional source of atmospheric pollution. Building demolition, earthworks, and the production and transportation of construction materials are accompanied by the generation of

⁷ Боголюбов В. М., Клименко М. О., Мокін В. Б. та ін. Моніторинг довкілля : підручник. Херсон : Грінь Д. С., 2011. 530 с.

substantial amounts of PM_{10} and $PM_{2.5}$. Where dust suppression systems are not applied, particulate matter concentrations in adjacent areas may exceed recommended limits severalfold.

At the same time, urbanized areas create specific microclimatic conditions known as the urban heat island effect. Elevated air temperatures, reduced wind speeds, and high building density contribute to the accumulation of pollutants in the near-surface atmospheric layer and intensify photochemical reactions. This results in more intensive formation of ground-level ozone and secondary aerosols, particularly during the summer period.

Military Activities as an Emerging Factor of Technogenic Atmospheric Air Pollution

One of the most pressing environmental issues of the twenty-first century is the impact of armed conflicts on atmospheric air quality. Unlike conventional sources of technogenic pressure, military activities are characterized by the extreme intensity, unpredictability, and complexity of pollution processes. The destruction of industrial enterprises, energy infrastructure, fuel and lubricant storage facilities, residential buildings, and transport hubs is accompanied by the large-scale release of a wide range of toxic substances into the atmosphere.

A distinctive feature of wartime pollution is the simultaneous generation of large quantities of both primary and secondary pollutants. Fires and explosions release nitrogen oxides, sulfur oxides, carbon monoxide, fine particulate matter, black carbon, polycyclic aromatic hydrocarbons, dioxins, heavy metals, and numerous organic toxicants into the atmosphere. The destruction of buildings is accompanied by the generation of mineral dust, which may contain cement, asbestos, quartz, lead, residues of paints and coatings, and other hazardous components.

For Ukraine, this problem has become particularly acute. The full-scale war has placed unprecedented pressure on atmospheric air as a result of fires at oil depots, the destruction of industrial facilities, explosions at ammunition depots, wildfires, attacks on energy infrastructure, and the intensive use of military equipment. It is important to emphasize that the consequences of such events are not confined to the areas in which they occur. Due to atmospheric circulation, fine particulate aerosols and gaseous pollutants can be transported over hundreds or even thousands of kilometres, creating transboundary environmental risks^{8, 9}.

⁸ Скок А., Хрутьба В. Якість атмосферного повітря в Україні до і під час повномасштабного вторгнення. Міжнародний фонд відродження. Київ, 2023. С. 5–24.

⁹ Хондак І., Стищенко Т. Забруднення атмосферного повітря в умовах війни в Україні. Біологічні, хімічні та екологічні загрози під час війни : колективна монографія / за заг. ред. В. В. Поповича, В. О. Сергієнка, Н. О. Іванченко. Львів : ЛДУБЖД, 2025. С. 391–399.

An analysis of the contemporary structure of anthropogenic sources of atmospheric air pollution indicates that technogenic pressure results from the interaction of numerous economic sectors, each characterized by a specific spectrum of emissions and mechanisms of atmospheric transformation. Whereas in the second half of the twentieth century large stationary industrial enterprises played the dominant role, the current period is characterized by a transition towards a multicomponent pollution model in which diffuse sources, urbanized environments, transport, the agricultural sector, and military activities are becoming increasingly important. This transformation requires a revision of traditional approaches to atmospheric air monitoring, a transition towards integrated air quality management systems, and consideration of the interrelationships among local emission sources, the transboundary transport of pollutants, and global climate processes.

Volatile Organic Compounds (VOCs) as Precursors of Secondary Atmospheric Pollution

Among the wide range of anthropogenic atmospheric pollutants, volatile organic compounds (VOCs) occupy a special place, representing one of the largest and most diverse groups of organic substances present in the atmosphere. To date, more than 10,000 organic compounds capable of existing in the gaseous phase of the atmosphere have been identified; however, only a small proportion of them are systematically monitored within national monitoring programmes¹⁰.

A distinctive feature of VOCs is that most of them are not among the most toxic components of atmospheric air in their primary form. Their environmental hazard is primarily determined by their high photochemical reactivity and their ability to participate in complex atmospheric oxidation reactions, resulting in the formation of ground-level ozone, peroxyacetyl nitrate (PAN), secondary organic aerosols (SOAs), organic peroxides, and other oxygen-containing organic compounds¹¹.

Photochemical Processes and the Formation of Secondary Organic Aerosols

Over the past two decades, the understanding of atmospheric chemistry has changed substantially. Whereas aerosol particles were previously regarded primarily as products of the mechanical fragmentation of materials or combustion processes, contemporary research demonstrates that a significant proportion of atmospheric aerosols is formed directly within the atmosphere as a result of photochemical reactions¹².

¹⁰ Seinfeld J. H., Pandis S. N. Atmospheric Chemistry and Physics: From Air Pollution to Climate Change. 3rd ed. Hoboken : John Wiley & Sons, 2016. 1152 p.

¹¹ World Health Organization. WHO Global Air Quality Guidelines: Particulate Matter (PM_{2.5} and PM₁₀), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. Geneva : WHO, 2021. 290 p.

¹² Seinfeld J. H., Pandis S. N. Atmospheric Chemistry and Physics: From Air Pollution to Climate Change. 3rd ed. Hoboken : John Wiley & Sons, 2016. 1152 p.

In recent years, it has been established that secondary organic aerosols not only deteriorate atmospheric air quality but also actively influence the Earth's climate system. They alter the optical properties of the atmosphere, scatter and absorb solar radiation, act as cloud condensation nuclei, and modify precipitation formation processes.

Despite significant progress in the study of atmospheric chemistry, the mechanisms underlying the formation of secondary organic aerosols remain among the most complex issues in contemporary atmospheric environmental science. The quantitative contributions of anthropogenic and biogenic VOCs to SOA formation, the role of multiphase reactions within aerosol droplets, the influence of climate change on the rates of photochemical processes, and the interactions between organic aerosols and black carbon remain subjects of scientific debate. For this reason, international research programmes and initiatives such as ACTRIS, the Copernicus Atmosphere Monitoring Service (CAMS), and the Global Atmosphere Watch (GAW/WMO) place particular emphasis on improving atmospheric chemistry models and integrating ground-based and satellite observations^{13 14 15}.

Heavy Metals in Atmospheric Air: Sources, Chemical Forms, Atmospheric Transport, and Environmental Risks

Heavy metals are among the most hazardous components of technogenic atmospheric air pollution because they combine high toxicity, environmental persistence, the ability to bioaccumulate, and a virtually unlimited persistence within natural biogeochemical cycles. Unlike most gaseous pollutants, which are gradually degraded or transformed in the atmosphere, metal atoms are not subject to biochemical degradation. Only their physicochemical forms, oxidation states, solubility, and bioavailability change, largely determining their toxicological properties and environmental hazards¹⁶.

In contemporary atmospheric environmental science, the concept of potentially toxic elements (PTEs) is increasingly used as a broader term than the traditional designation "heavy metals". This is because the environmental hazard posed by a substance is determined not only by its atomic mass but primarily by its toxicity, bioavailability, ability to accumulate in living organisms, and involvement in biogeochemical processes. This group includes lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), nickel

¹³ IPCC. *Climate Change 2023: Synthesis Report*. Geneva, 2023.

¹⁴ European Environment Agency. *Air Quality Status Report 2025*. Luxembourg : Publications Office of the European Union, 2025.

¹⁵ European Commission. *Zero Pollution Action Plan: Towards Zero Pollution for Air, Water and Soil*. Brussels : European Commission, 2021.

¹⁶ European Environment Agency. *Air Quality Status Report 2025*. Luxembourg : Publications Office of the European Union, 2025.

(Ni), cobalt (Co), copper (Cu), zinc (Zn), vanadium (V), manganese (Mn), and other elements that enter the atmosphere predominantly as a result of anthropogenic activities¹⁷.

The principal sources of atmospheric heavy metal emissions remain thermal power generation, metallurgical production, non-ferrous metallurgy, the cement industry, waste incineration, mining and mineral processing, transport, and certain technological processes within the chemical industry.

One of the most important findings of contemporary atmospheric ecotoxicology has been the recognition that the greatest hazard is posed not by metals alone, but by their association with fine particulate aerosols. PM_{2.5} particles have an exceptionally large specific surface area onto which lead, cadmium, nickel, arsenic, and other elements can be adsorbed. As a result, multicomponent aerosols are formed that simultaneously combine the physical effects of fine particulate matter with the toxic effects of adsorbed substances.

2. Fine Particulate Matter (PM₁₀, PM_{2.5}) and Its Transboundary Transport

Over the past two decades, the problem of fine particulate aerosol pollution of atmospheric air has become one of the leading global environmental challenges. Whereas in the second half of the twentieth century scientific attention was focused primarily on the study of sulfur oxides, nitrogen oxides, and carbon monoxide, contemporary research increasingly emphasizes atmospheric particulate matter with small aerodynamic diameters. This is primarily because fine particulate matter, particularly PM₁₀ and PM_{2.5}, is associated with some of the most pronounced adverse effects on public health, the functioning of natural ecosystems, regional climate processes, and the economic development of countries^{18, 19}.

Fine atmospheric particulate matter is among the most compositionally complex components of atmospheric air. Unlike gaseous pollutants, solid aerosol particles are not individual chemical substances but rather multicomponent mixtures of mineral, organic, and biological constituents. Their relative proportions are determined by the nature of emission sources, meteorological conditions, atmospheric photochemical processes, and the residence time of particles in the atmosphere.

¹⁷ World Health Organization. WHO Global Air Quality Guidelines: Particulate Matter (PM_{2.5} and PM₁₀), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. Geneva : WHO, 2021. 290 p.

¹⁸ World Health Organization. WHO Global Air Quality Guidelines: Particulate Matter (PM_{2.5} and PM₁₀), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. Geneva : WHO, 2021. 290 p.

¹⁹ IPCC. *Climate Change 2023: Synthesis Report*. Geneva, 2023.

According to the recommendations of the World Health Organization and the European Environment Agency, atmospheric aerosols are classified primarily according to their aerodynamic diameter, which determines their atmospheric transport characteristics, deposition rates, and depth of penetration into the human body^{20, 21}.

The PM₁₀ category includes particles with an aerodynamic diameter of up to 10 µm. These particles are predominantly deposited in the upper respiratory tract, although their finer fractions may penetrate into the bronchi and bronchioles. PM_{2.5} particles, with an aerodynamic diameter not exceeding 2.5 µm, are capable of reaching the pulmonary alveoli, crossing the alveolar–capillary barrier, and entering the systemic circulation. For this reason, PM_{2.5} is considered one of the most hazardous environmental risk factors for human health.

In recent years, increasing attention has been devoted to the study of ultrafine particles (UFPs, PM_{2.5}), with diameters of less than 100 nm. Despite their relatively minor contribution to the total mass of atmospheric aerosols, they are characterized by an exceptionally large specific surface area and high chemical reactivity. Such particles are capable of penetrating not only into the circulatory system but also into the central nervous system via the olfactory nerve, a process that has been associated with the development of neurodegenerative diseases.

Chemical Composition of Fine Particulate Matter

Contemporary studies demonstrate that the chemical composition of PM_{2.5} and PM₁₀ varies substantially depending on the region, season, and predominant emission sources. Nevertheless, in most urbanized areas, fine particulate matter typically contains the following components: sulfates (SO₄²⁻); nitrates (NO₃⁻); ammonium (NH₄⁺); organic carbon (OC); black carbon (BC); mineral components (Si, Al, Ca, Fe); heavy metals (Pb, Cd, Hg, As, Ni, Cr); polycyclic aromatic hydrocarbons; and biological components (pollen, bacteria, and fungal spores).

The relative proportions of these components represent a distinctive “chemical fingerprint” of pollution sources. For example, elevated concentrations of black carbon and organic carbon are characteristic of transport emissions and combustion processes, whereas high concentrations of calcium, silicon, and aluminium generally indicate contributions from soil dust or construction activities. The presence of vanadium and nickel may serve as an indicator of

²⁰ World Health Organization. WHO Global Air Quality Guidelines: Particulate Matter (PM_{2.5} and PM₁₀), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. Geneva : WHO, 2021. 290 p.

²¹ European Environment Agency. Air Quality Status Report 2025. Luxembourg : Publications Office of the European Union, 2025.

heavy fuel oil combustion, while lead, cadmium, or zinc may indicate emissions from metallurgical production or waste incineration²².

One of the most important concepts in contemporary atmospheric chemistry is the classification of aerosols into primary and secondary aerosols.

Primary aerosols are emitted directly into the atmosphere from emission sources. These include dust generated during industrial processes, transport activities, construction, mining, biomass combustion, and fossil fuel combustion. Primary aerosols may also originate from natural sources, including sea spray aerosols, dust storms, and volcanic ash.

Secondary aerosols are formed directly in the atmosphere as a result of chemical reactions involving gaseous precursors, including sulfur oxides, nitrogen oxides, ammonia, and volatile organic compounds. They often account for a substantial proportion of the PM₁₀ mass in European cities. This fact is of fundamental importance for environmental policy, since effectively reducing PM_{2.5} concentrations requires not only the reduction of direct particulate emissions but also the mitigation of emissions of gaseous precursors.

Transboundary Transport of Fine Particulate Matter: Mechanisms, Modelling, and Environmental Consequences²²

One of the most important characteristics of fine particulate matter, including PM₁₀ and PM_{2.5}, is its ability to be transported over considerable distances by atmospheric airflows. Whereas larger aerosol particles generally settle relatively close to their emission sources, fine particulate matter may remain suspended in the atmosphere for several days or even weeks, travelling hundreds or thousands of kilometres. As a result, atmospheric pollution is no longer merely a local or even national problem but acquires a transboundary dimension, requiring international coordination of environmental policies^{23, 24}.

In contemporary atmospheric science, transboundary transport is defined as the movement of gaseous and aerosol pollutants across national borders under the influence of large-scale atmospheric circulation. The intensity of this process depends on the physicochemical properties of the particles, the altitude at which they enter the atmosphere, wind speed and direction, atmospheric temperature stratification, turbulent mixing, precipitation levels, and the atmospheric residence time of aerosols.

²² Seinfeld J. H., Pandis S. N. Atmospheric Chemistry and Physics: From Air Pollution to Climate Change. 3rd ed. Hoboken : John Wiley & Sons, 2016. 1152 p.

²³ World Health Organization. WHO Global Air Quality Guidelines: Particulate Matter (PM_{2.5} and PM₁₀), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. Geneva : WHO, 2021. 290 p.

²⁴ European Commission. Zero Pollution Action Plan: Towards Zero Pollution for Air, Water and Soil. Brussels : European Commission, 2021.

PM_{2.5} particles are characterized by considerably greater mobility than PM₁₀ particles. Due to their small aerodynamic diameter, they have a low gravitational settling velocity, which enables them to remain suspended in the atmosphere for extended periods. Consequently, fine particulate matter can be transported over long distances even in the absence of major emission sources in regions where elevated concentrations are recorded. This characteristic explains why atmospheric air quality in one country may depend to a considerable extent on emission levels in neighbouring countries.

The transport of atmospheric aerosols results from the simultaneous action of several physical processes. Advection, turbulent diffusion, convective mixing, and gravitational settling play the most important roles.

Meteorological Factors Influencing Transboundary Transport

The efficiency of fine particulate matter transport is largely determined by meteorological conditions. The most important factors include wind speed and direction, the height of the planetary boundary layer, air temperature, relative humidity, the intensity of solar radiation, and precipitation.

The height of the atmospheric boundary layer plays a particularly important role. During the daytime, when the boundary layer becomes deeper, pollutants are actively mixed and dispersed. At night or under anticyclonic conditions, the boundary layer becomes shallower, resulting in the accumulation of aerosols near the Earth's surface and a marked deterioration in air quality.

Climate change is another important factor. According to the IPCC, rising temperatures, the increasing frequency of prolonged droughts, and large-scale wildfires can substantially alter the spatial distribution of atmospheric aerosols. Furthermore, climate change affects the rates of photochemical reactions responsible for the formation of secondary PM_{2.5}²⁵.

For Ukraine, the issue of transboundary transport is of particular importance due to the country's geographical location in the centre of Europe and the presence of major industrial regions in neighbouring countries. Scientific studies conducted by the Ukrainian Hydrometeorological Institute of the State Emergency Service of Ukraine and the National Academy of Sciences of Ukraine, the Borys Sreznevskyi Central Geophysical Observatory, as well as within the framework of cooperation with the EMEP programme, confirm that fine particulate matter concentrations in Ukraine are influenced by both domestic emission sources and atmospheric transport from the territories of other countries²⁶.

²⁵ IPCC. *Climate Change 2023: Synthesis Report*. Geneva, 2023.

²⁶ Огляд стану забруднення навколишнього природного середовища на території України за даними мережі моніторингу гідрометеорологічних організацій у 2024 році.

URL: <http://cgo-sreznevskyi.kyiv.ua/uk/diialnist/khimichne-zabrudnennia/8-materialy-na-glavnoj/171-stan-zabrudnennya-prirodnogo-seredovishcha-na-teritoriji-ukrajini>.

Since 2022, the nature of transboundary transport has become considerably more complex due to large-scale fires, the destruction of industrial enterprises, fuel and lubricant storage facilities, and energy infrastructure. Satellite observations conducted by Copernicus and NASA have repeatedly recorded the transport of aerosol plumes generated by fires beyond the borders of Ukraine. This highlights the need to integrate the national monitoring system with pan-European observation networks and to develop joint programmes for modelling atmospheric processes.

3. Environmental Monitoring of Atmospheric Air

Effective air quality management is impossible without a modern environmental monitoring system capable of providing reliable, timely, and spatially representative information on the state of the atmospheric environment. Over recent decades, the concept of monitoring has undergone substantial transformation. Whereas in the past its primary objective was the periodic measurement of concentrations of individual pollutants, the contemporary approach is based on the integration of continuous measurements, mathematical modelling, Earth remote sensing, geoinformation technologies, and tools for analysing large datasets^{27, 28}.

According to the definition provided by the United Nations Environment Programme (UNEP), environmental monitoring of atmospheric air is a comprehensive system of regular observations, analysis, assessment, and forecasting of atmospheric conditions aimed at the timely identification of adverse trends, assessment of environmental risks, and provision of information to support environmental policy. Thus, contemporary monitoring performs not only an informational function but also predictive and management functions.

In accordance with the requirements of Directive 2008/50/EC of the European Parliament and of the Council on ambient air quality and cleaner air for Europe, monitoring systems should ensure the measurement of concentrations of major atmospheric pollutants, including PM_{2.5}, PM₁₀, nitrogen dioxide (NO₂), sulfur dioxide (SO₂), ground-level ozone (O₃), carbon monoxide (CO), benzene (C₆H₆), lead, and other toxic components. Particular attention is paid to the spatial representativeness of observations, the standardization of measurement methods, and ensuring the comparability of results across different countries²⁹.

²⁷ World Health Organization. WHO Global Air Quality Guidelines: Particulate Matter (PM_{2.5} and PM₁₀), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. Geneva : WHO, 2021. 290 p.

²⁸ European Environment Agency. Air Quality Status Report 2025. Luxembourg : Publications Office of the European Union, 2025.

²⁹ Directive (EU) 2024/2881 of the European Parliament and of the Council of 23 October 2024 on ambient air quality and cleaner air for Europe (recast). *Official Journal of the European Union*. 2024.

International Atmospheric Air Monitoring Systems

Several global observation systems currently operate worldwide, providing the information base required for assessing atmospheric air quality.

The World Meteorological Organization coordinates the Global Atmosphere Watch (GAW) programme, which integrates hundreds of ground-based observation stations across different regions of the world. The programme provides long-term measurements of greenhouse gas concentrations, aerosols, ozone, and other atmospheric constituents³⁰.

Within the European Union, the Copernicus Atmosphere Monitoring Service (CAMS) plays a central role, integrating data from satellite observations, ground-based monitoring, and numerical modelling. CAMS provides daily air quality forecasts, assesses the transboundary transport of pollutants, and analyses the impacts of large-scale natural and anthropogenic events³¹.

The EMEP programme also plays an important role, providing the scientific basis for the implementation of the Convention on Long-range Transboundary Air Pollution (CLRTAP). Its primary objectives are to assess the flows of atmospheric pollutants between countries, analyse the effectiveness of environmental protection measures, and support environmental policy development in European countries.

Ukrainian Atmospheric Air Monitoring System

In Ukraine, state monitoring of atmospheric air is carried out in accordance with the Law of Ukraine “On Atmospheric Air Protection,” the Law of Ukraine “On Environmental Protection,” and the Procedure for State Monitoring in the Field of Atmospheric Air Protection. An important role in the development of the national monitoring system is played by the Ukrainian Hydrometeorological Center, the Ukrainian Hydrometeorological Institute of the State Emergency Service of Ukraine and the National Academy of Sciences of Ukraine, the Borys Sreznevskiy Central Geophysical Observatory, as well as regional monitoring laboratories^{32, 33, 34, 35}.

³⁰ World Meteorological Organization. State of Global Air Quality and Climate. Geneva : WMO, 2024.

³¹ European Centre for Medium-Range Weather Forecasts. Copernicus Atmosphere Monitoring Service (CAMS): Global and Regional Air Quality Products. Reading: ECMWF, 2024.

³² Про Основні засади (стратегію) державної екологічної політики України на період до 2030 року : Закон України від 28 лютого 2019 року № 2697-VIII. URL: <https://zakon.rada.gov.ua/go/2697-19>.

³³ Огляд стану забруднення навколишнього природного середовища на території України за даними мережі моніторингу гідрометеорологічних організацій у 2024 році. URL: <http://cgo-sreznevskiy.kyiv.ua/uk/diialnist/khimichne-zabrudnennia/8-materialy-na-glavnoj/171-stan-zabrudnennya-prirodnogo-seredovishcha-na-teritoriji-ukrajini>.

³⁴ Про Основні засади (стратегію) державної екологічної політики України на період до 2030 року : Закон України від 28 лютого 2019 року № 2697-VIII. URL: <https://zakon.rada.gov.ua/go/2697-19>.

³⁵ Про охорону атмосферного повітря : Закон України від 16 жовтня 1992 р. № 2707-XII. *Відомості Верховної Ради України*. 1992. № 50. С. 678.

In recent years, automated observation networks, municipal air quality monitoring systems, and community-based initiatives using low-cost sensors have been actively developing in Ukraine. At the same time, one of the major challenges remains the harmonization of the national monitoring system with European standards, the expansion of the network of automatic monitoring stations, the provision of open access to environmental information, and the integration of Ukrainian data into international information platforms.

Environmental monitoring of atmospheric air has evolved from a system of local observations into a complex digital network that combines automated measurements, satellite data, mathematical modelling, and geoinformation technologies. The integration of heterogeneous data sources provides a contemporary framework for air quality assessment and creates the necessary conditions for a transition from responding to existing pollution to forecasting and preventing it.

Automated Air Quality Monitoring Systems and Sensor Networks

The rapid development of information technologies, the automation of measurement processes, and the digitalization of environmental information have contributed to the emergence of a new generation of atmospheric air monitoring systems. Whereas traditional environmental monitoring methods involved periodic sampling followed by laboratory analysis, modern automated systems provide continuous real-time measurements of pollutant concentrations, rapid data transmission, and their integration into unified information and analytical platforms^{36, 37}.

Modern automated environmental monitoring stations are sophisticated technological systems equipped with gas analysers, particulate matter monitors, meteorological sensors, automatic calibration systems, and telemetry equipment. The principal advantage of such stations is their ability to continuously monitor changes in atmospheric pollutant concentrations, making it possible to detect episodes of high pollution in a timely manner, analyse their causes, and forecast the subsequent development of air quality conditions.

In European Union countries, automated monitoring networks operate in accordance with the requirements of Directive 2008/50/EC and the harmonized EN standards. This ensures the comparability of results across countries, high measurement accuracy, and the possibility of integrating data into the European Environment Information and Observation Network (Eionet)³⁸.

³⁶ World Health Organization. WHO Global Air Quality Guidelines: Particulate Matter (PM_{2.5} and PM₁₀), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. Geneva : WHO, 2021. 290 p.

³⁷ European Environment Agency. Air Quality Status Report 2025. Luxembourg : Publications Office of the European Union, 2025.

³⁸ Directive (EU) 2008/50 of the European Parliament and of the Council of 23 October 2008 on ambient air quality and cleaner air for Europe (recast). *Official Journal of the European Union*. 2008.

Reference Methods for Measuring Atmospheric Air Quality

One of the fundamental requirements of contemporary environmental monitoring is the use of reference measurement methods that ensure high accuracy, reproducibility, and metrological traceability of results.

One of the most important trends of the past decade has been the widespread adoption of low-cost sensors, which have substantially expanded the capabilities of environmental monitoring. The cost of such devices is many times lower than that of professional reference monitoring stations, making it possible to establish dense observation networks within cities, industrial zones, and transport corridors.

Sensor networks are primarily based on laser optical sensors that determine aerosol particle concentrations by measuring the intensity of light scattering. They may additionally be equipped with electrochemical sensors for measuring NO₂, SO₂, CO, and O₃, as well as sensors for temperature, humidity, atmospheric pressure, and wind speed.

Alongside the development of stationary networks, mobile monitoring systems are becoming increasingly important. Measurement equipment is installed on cars, public transport vehicles, bicycles, and even personal devices, making it possible to obtain highly detailed spatial maps of air pollution.

A particularly promising area is the use of unmanned aerial vehicles (UAVs). Equipped with compact gas analysers and particulate matter monitors, drones can perform measurements at different altitudes and investigate areas surrounding industrial facilities, waste disposal sites, fire-affected areas, or accident sites. For Ukraine, this approach is becoming particularly relevant due to the need for rapid environmental assessment of territories affected by military activities.

In Ukraine, the modernization of atmospheric air monitoring systems is gradually gaining momentum. Alongside the state observation network, municipal automated monitoring stations, regional information systems, and community-based sensor networks are being actively developed. Local authorities, universities, research institutions, and non-governmental organizations make a significant contribution to the implementation of modern monitoring technologies.

At the same time, a number of challenges remain, including the insufficient density of automatic monitoring stations, limited funding, varying levels of metrological support, and the need to harmonize measurement methodologies with European standards. The further development of Ukraine's monitoring system should involve the integration of state, municipal, and community-based networks, the establishment of a unified digital platform for environmental data, and the expanded use of modern information technologies.

Automated atmospheric air monitoring systems form the foundation of contemporary environmental management. The integration of reference monitoring stations, sensor networks, Internet of Things (IoT) technologies, mobile platforms, and unmanned aerial vehicles creates a multi-level observation system capable of ensuring the rapid detection of pollution, forecasting its development, and providing information support for environmental management decisions. For Ukraine, the modernization of such systems is an important prerequisite for alignment with European standards, improving the effectiveness of environmental monitoring and control, and supporting post-war environmental recovery³⁹.

Conceptual Framework for Remote Monitoring of Atmospheric Air

The rapid development of space technologies over the past two decades has substantially transformed approaches to atmospheric air quality assessment. Whereas traditional monitoring systems are primarily based on networks of stationary ground-based observation stations, modern satellite systems make it possible to obtain information on the spatial distribution of atmospheric pollutants on an almost global scale. The integration of ground-based measurements with remote sensing data provides a fundamentally new level of environmental monitoring, which is particularly important for assessing the transboundary transport of pollutants and analysing large-scale wildfires, dust storms, volcanic eruptions, and other major natural and anthropogenic events^{40, 41}.

The principal advantage of satellite monitoring is its ability to simultaneously observe vast areas, including remote and difficult-to-access regions, marine areas, and border zones. This makes it possible to obtain a comprehensive picture of atmospheric conditions that cannot be provided solely by ground-based measurements. Furthermore, satellite observations are particularly important for countries with insufficiently developed networks of automated monitoring stations, as they can partially compensate for the lack of ground-based data.

At the same time, the contemporary scientific community emphasizes that satellite data cannot fully replace ground-based measurements. Satellite observations characterize the integrated state of the atmospheric column or individual atmospheric layers and therefore require validation against ground-based monitoring data. For this reason, an integrated approach combining

³⁹ Моніторинг забруднення повітря на території України. URL: <https://www.saveecobot.com/maps/kharkiv>).

⁴⁰ European Environment Agency. Air Quality Status Report 2025. Luxembourg : Publications Office of the European Union, 2025.

⁴¹ World Meteorological Organization. State of Global Air Quality and Climate. Geneva : WMO, 2024.

remote sensing data, automated monitoring stations, mathematical modelling, and geoinformation analysis is considered the most effective.

Integration of Satellite and Ground-Based Observations

One of the key trends in contemporary atmospheric science is the integration of satellite information with data obtained from automated ground-based monitoring stations. This approach makes it possible to compensate for the limitations inherent in each method when used separately. Ground-based measurements provide high accuracy in determining pollutant concentrations in the near-surface atmospheric layer, whereas satellite observations enable the analysis of their spatial distribution on regional and global scales.

To integrate heterogeneous sources of information, geographic information systems (GIS), spatial interpolation methods, data assimilation techniques, and machine-learning algorithms are being increasingly applied. These approaches make it possible to generate highly detailed maps of $PM_{2.5}$, PM_{10} , and other pollutant concentrations even in regions with an insufficient number of ground-based monitoring stations.

Satellite Monitoring under Wartime Conditions

For Ukraine, remote sensing of the atmosphere has acquired particular importance since 2022. Data from Sentinel-5P, MODIS, and VIIRS satellite instruments are extensively used to detect large-scale fires, assess the dispersion of smoke plumes, and analyse the consequences of damage to industrial facilities, oil depots, and energy infrastructure. The integration of satellite data with atmospheric transport models makes it possible to assess potential pollutant dispersion pathways and forecast their impacts on the territory of Ukraine and neighbouring countries.

Furthermore, remote sensing is an important tool for post-war environmental recovery. Satellite observations can be used to assess long-term changes in atmospheric air quality, monitor the effectiveness of environmental protection measures, and support the development of environmental policy at the national level.

The most advanced monitoring systems are gradually evolving from separate information platforms into integrated environmental ecosystems.

Their structure includes automated monitoring stations; networks of low-cost sensors; unmanned aerial vehicles (UAVs); Copernicus and NASA satellite systems; atmospheric mathematical models; geographic information systems (GIS); artificial intelligence algorithms; digital twins of territories; and cloud-based data processing services.

It is precisely the integration of all these components that enables the transition from passive observation to proactive environmental management, in which the system not only detects pollution but also forecasts its development,

proposes potential response scenarios, and assesses the effectiveness of management decisions.

For Ukraine, the implementation of artificial intelligence, Big Data, and digital twin technologies represents one of the most promising directions for modernizing the national environmental monitoring system. This is particularly relevant in the context of post-war recovery, when there is a need to rapidly assess atmospheric air quality, monitor the environmental consequences of damage to industrial facilities, model the dispersion of pollutants, and provide a scientific basis for environmental protection measures.

Promising directions for further development include the integration of Ukrainian monitoring systems with the Copernicus and CAMS platforms; the application of artificial intelligence algorithms for forecasting PM_{2.5} concentrations; the development of digital twins for Ukraine's largest cities; the establishment of a national open environmental data platform; and the use of unmanned aerial vehicles for rapid environmental monitoring^{42, 43}.

Global Trends in Atmospheric Air Pollution and the Development of Monitoring Systems

According to research conducted by IQAir, an international company that annually assesses atmospheric air quality using data from a global network of monitoring stations, air pollution remains one of the most serious environmental threats of the modern era. Analysis of data from more than 30,000 monitoring stations located in thousands of settlements across different countries indicates systematic exceedances of the guideline levels for fine particulate matter (PM_{2.5}) recommended by the World Health Organization (WHO).

The analysis presented in the 2025 World Air Quality Report confirms the persistence of adverse trends. The report was based on data from monitoring stations located in 9,446 cities across 143 countries, territories, and regions worldwide, providing the broadest geographical coverage achieved over the entire period of such assessments. Compared with the previous year, the monitoring network was expanded to include additional countries and territories, thereby improving the representativeness of the global assessment of atmospheric air quality.

The results demonstrate that only 14% of cities worldwide met the WHO guideline for annual mean PM_{2.5} concentrations, while 91% of countries and territories exceeded the recommended level. These findings highlight the global

⁴² Моніторинг забруднення повітря на території України. URL: <https://www.saveecobot.com/maps/kharkiv>).

⁴³ Огляд стану забруднення навколишнього природного середовища на території України за даними мережі моніторингу гідрометеорологічних організацій у 2024 році. URL: <http://cgo-sreznivskiy.kyiv.ua/uk/diialnist/khimichne-zabrudnennia/8-materialy-na-glavnoj/171-stan-zabrudnennya-prirodnoho-seredovishcha-na-teritoriji-ukrajini>.

nature of the problem and the need for further improvement of environmental policies at the international level⁴⁴.

The countries with the highest levels of atmospheric air pollution include Pakistan, Bangladesh, Tajikistan, Chad, and the Democratic Republic of the Congo, where annual mean PM_{2.5} concentrations exceed WHO recommendations severalfold. Loni, India, was identified as the world's most polluted city, with an annual mean PM_{2.5} concentration of 112.5 µg/m³, more than twenty times higher than the recommended level. In contrast, the lowest concentration of fine particulate matter was recorded in Nieuwoudtville, South Africa, where the annual mean PM_{2.5} concentration was only 1.0 µg/m³.

A distinctive feature of 2025 was that all twenty-five of the world's most polluted cities were located in India, Pakistan, and China, confirming the exceptionally high concentration of environmental risks in South and East Asia. At the same time, for the second consecutive year, no city in East Asia met the WHO guideline for annual mean PM_{2.5} concentrations.

Regional analysis revealed considerable variation in air quality trends. In Europe, annual mean PM_{2.5} concentrations increased in 23 countries in 2025, while decreases were recorded in 18 countries. Seasonal deterioration in air quality was significantly influenced by residential wood burning for heating, the transboundary transport of smoke from large-scale wildfires in Canada, and the transport of dust masses from the Sahara Desert.

Countries in Latin America and the Caribbean generally demonstrated a positive trend, with annual mean PM_{2.5} concentrations decreasing in most cities. Oceania remained one of the cleanest regions in the world, with more than 60% of cities meeting WHO recommendations, although certain climatic events caused short-term seasonal deterioration in air quality.

One of the major factors contributing to the deterioration of atmospheric air quality in 2025 was the occurrence of large-scale wildfires, the increasing intensity of which is closely associated with climate change. Substantial emissions from biomass burning resulted in the transboundary transport of pollutants and the deterioration of atmospheric air quality across extensive areas of North America and Europe. In particular, smoke from wildfires in Canada adversely affected air quality not only within Canada itself but also in the United States and several European countries.

The report also places particular emphasis on the development of global atmospheric air monitoring systems. The discontinuation in 2025 of the air quality monitoring programme supported by the U.S. Department of State

⁴⁴ Звіт про якість повітря IQAir у світі за 2025 рік. URL: <https://www.iqair.com/newsroom/waqr-2025-pr>.

through its network of embassies and consulates resulted in a reduction in the availability of open environmental data in many countries. According to estimates by the Centre for Research on Energy and Clean Air (CREA), monitoring capacity was weakened in 44 countries, while six countries were temporarily left without functioning air quality monitoring networks.

These trends confirm that effective atmospheric air quality management is impossible without the development of a modern environmental monitoring system. Particular importance is attached to the implementation of automated observation networks, the use of affordable sensor technologies, digital platforms for processing environmental information, geographic information systems, and artificial intelligence tools. The expansion of monitoring networks enables the timely acquisition of reliable information on atmospheric air quality, facilitates the early identification of environmental risks, enhances the effectiveness of environmental policy, and provides a scientific basis for informed management decisions aimed at reducing the adverse impacts of atmospheric pollution on public health and the environment⁴⁵.

Atmospheric Air Pollution in Ukraine: Current Challenges and Mitigation Strategies

The main anthropogenic sources of atmospheric air pollution in Ukraine are stationary and mobile sources. Stationary sources include industrial enterprises, thermal power plants, boiler facilities, production complexes, and other facilities whose activities are associated with substantial volumes of emissions. Mobile sources are represented primarily by road transport, which in many cities accounts for a major share of atmospheric air pollution and significantly affects the quality of life of the population.

Statistical data indicate that between 2020 and 2025, substantial changes occurred in both the structure and total volume of emissions of pollutants and greenhouse gases in Ukraine. The analysis demonstrates the clear impact of wartime events, the structural transformation of the economy, and changes in the intensity of industrial activity⁴⁶.

In 2020, the total volume of emissions amounted to 3,675.3 thousand tonnes, representing one of the highest values recorded during the study period. In 2021, emissions from stationary sources decreased to 2,239.8 thousand tonnes, representing a reduction of approximately 39.1% compared with 2020 (3,675.3 thousand tonnes). This indicates that industrial pressure had already begun to decline before the sharp decrease in economic activity observed in 2022.

⁴⁵ Звіт про якість повітря IQAir у світі за 2025 рік. URL: <https://www.iqair.com/newsroom/waqr-2025-pr>.

⁴⁶ Державна служба статистики України. Викиди забруднюючих речовин і парникових газів у атмосферне повітря. URL: <https://www.ukrstat.gov.ua/>.

The most substantial changes occurred in 2022. Emissions from stationary sources decreased to 1,190.9 thousand tonnes, representing a reduction of almost half (–46.8%) compared with 2021. This decline can be attributed to the full-scale war, the loss of control over parts of major industrial regions, the destruction of production infrastructure, reductions in metallurgical and energy production, and decreased transport activity.

In 2023, emissions increased slightly to 1,225.9 thousand tonnes, which may be associated with the gradual adaptation of the economy to wartime conditions and the partial resumption of operations at certain enterprises.

In 2024, emissions decreased again to 997.8 thousand tonnes, after which they remained virtually stable at 998.4 thousand tonnes in 2025. The minimal difference between the 2024 and 2025 values indicates the emergence of a new, relatively stable level of anthropogenic pressure.

According to [1], the total volume of emissions from all sources amounted to 3,677.7 thousand tonnes in 2021. In 2022, it decreased to 2,990.6 thousand tonnes, followed by an increase to 3,053.1 thousand tonnes in 2023. In 2024, the indicator declined again to 2,845.5 thousand tonnes, before increasing slightly to 2,876.5 thousand tonnes in 2025.

Overall, over the five-year period, the total volume of emissions decreased by approximately 21.8%, indicating a substantial reduction in anthropogenic pressure on atmospheric air.

Specific emissions from stationary pollution sources characterize the intensity of environmental pressure per unit area of the country.

In 2021, this indicator amounted to 3,884.4 kg/km², whereas in 2022 it decreased to 2,065.4 kg/km², representing a reduction of almost 46.8%. In 2023, a slight increase to 2,126.1 kg/km² was recorded, followed by a decline to 1,730.5 kg/km² in 2024. The indicator remained virtually unchanged in 2025, amounting to 1,731.6 kg/km² (Table 2).

A similar trend can be observed in total specific emissions per unit area. While in 2021 they amounted to 6,378.2 kg/km², in 2022 they decreased to 5,186.5 kg/km². In 2023, a slight increase to 5,294.8 kg/km² was recorded; however, in 2024 the indicator reached its lowest value during the study period, at 4,934.9 kg/km². In 2025, only a minor increase to 4,988.6 kg/km² was observed (Table 2).

The results indicate that a new trend in atmospheric pollution dynamics emerged in Ukraine during 2020–2025. Following the sharp reduction in emissions in 2022, the indicators gradually stabilized at a lower level; however, this should not be interpreted as evidence of a substantial improvement in the environmental situation. The primary reason for the decline in emissions was not the widespread implementation of environmentally friendly technologies

or digital monitoring systems, but rather the reduction in industrial production, the destruction of production facilities, and structural changes in the economy resulting from the war.

At the same time, the relative stabilization of indicators in 2024–2025 creates preconditions for the transition towards a new model of environmental management. In the context of post-war recovery, the implementation of digital atmospheric air monitoring systems, automated observation networks, geographic information technologies, Earth remote sensing, and artificial intelligence tools is becoming particularly important. Their application will not only improve the timeliness and efficiency of atmospheric air quality monitoring but will also facilitate scientifically informed management decisions in the field of environmental protection and support the alignment of Ukraine’s environmental policy with European Union standards.

Prior to the onset of the full-scale war, the main hotspots of atmospheric air pollution in Ukraine were major industrial centres, including Mariupol, Kryvyi Rih, Zaporizhzhia, and Dnipro, where the predominant share of emissions originated from metallurgical, energy, and chemical industries. In Kyiv, the capital of Ukraine, road transport remained the principal source of atmospheric air pollution, contributing to high concentrations of nitrogen oxides, carbon monoxide, and particulate matter⁴⁷.

Table 2

Dynamics of Pollutant and Greenhouse Gas Emissions in Ukraine⁴⁸

Baseline Statistical Indicator	2021	2022	2023	2024	2025
Amount of pollutant and greenhouse gas emissions per unit area (stationary sources of pollution, kg/km ²)	3884.4	2065.4	2126.1	1730.5	1731.6
Amount of pollutant and greenhouse gas emissions per unit area (total, kg/km ²)	6378.2	5186.5	5294.8	4934.9	4988.6

The full-scale military aggression has caused substantial changes in the territorial distribution of industrial production. A considerable number of enterprises have been relocated to safer regions of the country; however, assessing their spatial distribution and the scale of their environmental impact is complicated by restricted access to certain state registers. As a result, environmental pressure is gradually shifting towards areas that were previously characterized by relatively favourable atmospheric air quality. These regions

⁴⁷ Хондак І., Стищенко Т. Забруднення атмосферного повітря в умовах війни в Україні. Біологічні, хімічні та екологічні загрози під час війни : колективна монографія / за заг. ред. В. В. Поповича, В. О. Сергієнка, Н. О. Іванченко. Львів : ЛДУБЖД, 2025. С. 391–399.

⁴⁸ Державна служба статистики України. Викиди забруднюючих речовин і парникових газів у атмосферне повітря. URL: <https://www.ukrstat.gov.ua/>.

include Ternopil, Lviv, and Volyn oblasts, where increasing industrial activity is accompanied by a growing potential risk of atmospheric pollution.

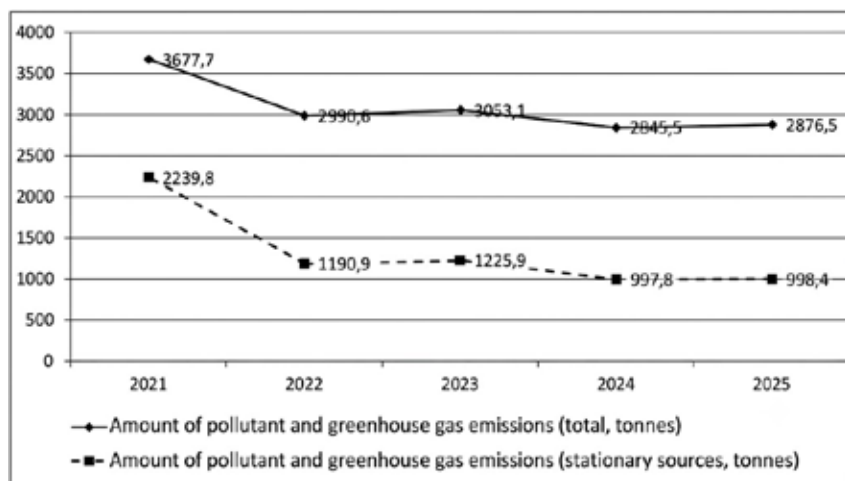


Fig. 1. Dynamics of pollutant and greenhouse gas emissions in Ukraine

Despite the challenging socio-economic and security conditions, atmospheric air pollution remains one of the most pressing environmental problems in Ukraine. Addressing this issue requires the implementation of a comprehensive set of organizational, technical, and management measures. For stationary pollution sources, priority measures include the modernization of technological processes, the introduction of highly efficient gas-cleaning systems, automated emission monitoring systems and digital environmental monitoring platforms, as well as improvements in the reporting system for pollutant emissions.

Reducing the adverse impact of mobile pollution sources can be achieved through the development of environmentally sustainable transport, an increase in the share of electric vehicles and low-emission vehicles, improvements in transport infrastructure, and incentives for the use of alternative fuels.

Environmental awareness among the population also plays an important role in ensuring environmental safety. Although individuals cannot substantially influence the scale of industrial emissions, they can monitor air quality in residential and occupational environments, use modern air purification technologies, and comply with safety requirements for the operation of autonomous energy supply systems. This issue has become particularly relevant due to the widespread use of generators, battery storage systems, and inverters,

the improper operation of which may lead to the accumulation of hazardous concentrations of combustion products and pose a threat to human health⁴⁹.

4. Atmospheric Pollution and Climate Change

For a long time, the problems of atmospheric air pollution and global climate change were regarded as two relatively independent areas of environmental research. Atmospheric pollution was traditionally associated primarily with local or regional impacts on public health, ecosystem functioning, and the state of the natural environment, whereas climate change was interpreted as a global process driven by the accumulation of greenhouse gases in the atmosphere. However, the findings of fundamental research conducted over recent decades have convincingly demonstrated that these processes are interconnected components of the Earth's integrated climate-atmosphere system^{50, 51}.

The development of the contemporary scientific concept of the relationship between atmospheric air quality and climate has been made possible by advances in atmospheric physics, atmospheric chemistry, climate modelling, and satellite monitoring. The reports of the Intergovernmental Panel on Climate Change (IPCC) have played a particularly important role, demonstrating that numerous atmospheric pollutants simultaneously affect both air quality and the energy balance of the climate system. This applies primarily to black carbon, tropospheric ozone, methane, and secondary aerosols, which contribute to radiative forcing and alter the properties of the atmosphere.

Contemporary environmental science considers the atmosphere as a single dynamic system in which physical, chemical, and biogeochemical processes are in constant interaction. Pollutants released into the atmosphere as a result of human activities not only deteriorate air quality but also alter atmospheric circulation patterns, cloud formation processes, the albedo of the Earth's surface, the intensity of solar radiation, and the global water cycle. At the same time, climate change affects the rates of photochemical reactions, the frequency of extreme weather events, the scale of wildfires, dust storms, and other processes that determine atmospheric pollutant concentrations. Thus, a complex bidirectional mechanism of interaction between atmospheric pollution and climate change is formed.

Contemporary International Scientific Framework

In the twenty-first century, international organizations have increasingly adopted an integrated approach according to which policies aimed at improving

⁴⁹ Новіков М. А., Хондак І. І. Проблема забруднення атмосферного повітря в Україні. *Радіоелектроніка та молодь у XXI столітті* : матеріали 29-го Міжнар. молодіж. форуму, 16–19 квітня 2025 р. Харків : ХНУРЕ, 2025. Т. 2. С. 132–134.

⁵⁰ IPCC. *Climate Change 2023: Synthesis Report*. Geneva, 2023.

⁵¹ World Meteorological Organization. *State of Global Air Quality and Climate*. Geneva : WMO, 2024.

atmospheric air quality and mitigating climate change should be regarded as complementary components of sustainable development.

The World Health Organization emphasizes that reducing emissions of fine particulate matter, nitrogen oxides, black carbon, and other atmospheric pollutants simultaneously contributes to improvements in public health and reductions in climate-related pressures. According to WHO estimates, the implementation of integrated clean-air policies has the potential to substantially reduce premature mortality associated with atmospheric pollution while simultaneously contributing to the fulfilment of international climate commitments.

Documents issued by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) emphasize that combating atmospheric air pollution is one of the most effective approaches to simultaneously achieving the environmental, social, and economic objectives of sustainable development. Particular importance is attached to reducing emissions of short-lived climate pollutants (SLCPs), among which black carbon, methane, and tropospheric ozone play a leading role^{52, 53}.

An important milestone was the publication of the IPCC Sixth Assessment Report (AR6), which confirmed that anthropogenic influence is the dominant driver of contemporary global warming. The report emphasizes that effectively limiting the increase in global mean temperature is impossible without comprehensive reductions in both greenhouse gas emissions and a range of atmospheric pollutants that directly affect the Earth's radiative balance.

The Ukrainian scientific community also devotes considerable attention to the interaction between atmospheric pollution and climate change. Ukrainian research institutions, including the Ukrainian Hydrometeorological Institute of the State Emergency Service of Ukraine and the National Academy of Sciences of Ukraine, the Borys Sreznevskyi Central Geophysical Observatory, and specialized universities, are actively developing research on atmospheric pollution assessment, climate modelling, the analysis of extreme weather events, and climate change adaptation. These studies have become particularly relevant under wartime conditions, which have substantially altered the structure of atmospheric pollution sources and created new challenges for environmental monitoring.

One of the most important trends in contemporary environmental policy is the transition towards integrated atmospheric environmental management. This approach implies that decisions concerning emission reductions, transport

⁵² World Meteorological Organization. State of Global Air Quality and Climate. Geneva : WMO, 2024.

⁵³ United Nations Environment Programme. Global Environment Outlook 6: Healthy Planet, Healthy People. Cambridge : Cambridge University Press, 2019. 708 p.

development, energy systems, industry, land use, and urban planning should simultaneously take into account their impacts on both air quality and the climate system.

The practical implementation of this concept is reflected in the European Green Deal, which aims to achieve climate neutrality by 2050, promote clean energy, reduce greenhouse gas emissions, modernize the transport system, and enhance the environmental resilience of cities. For Ukraine, integration into European environmental policy provides opportunities to modernize the atmospheric air monitoring system, develop a low-carbon economy, and implement contemporary nature-based solutions (NbS)⁵⁴.

An analysis of contemporary international and Ukrainian research indicates that atmospheric air pollution and global climate change should be considered interconnected processes within a single natural–anthropogenic system. Atmospheric pollutants can influence climatic conditions by altering the radiative balance, cloud formation, and biogeochemical cycles, while climate change modifies the conditions governing the formation, transformation, and dispersion of pollutants. Therefore, effective environmental policy in the twenty-first century should be based on an integrated approach combining measures to improve air quality, mitigate climate change, and adapt society to emerging environmental challenges.

Climate-Forming Role of Atmospheric Pollutants

The Earth's atmosphere is a complex physicochemical system in which energy transfer, substance transformation, and interactions among gaseous components, aerosols, clouds, and the underlying surface occur continuously. The release of anthropogenic pollutants into the atmosphere substantially alters these processes, affecting the radiative balance, atmospheric circulation, cloud formation, and the global water cycle. For this reason, contemporary climatology considers atmospheric pollutants not only as factors contributing to the deterioration of air quality but also as major drivers of transformations within the Earth's climate system⁵⁵.

The key mechanism underlying this influence is radiative forcing, which refers to a change in the balance between the energy received from the Sun and the energy emitted by the Earth back into space. If a particular substance increases the retention of thermal radiation in the atmosphere, it produces positive radiative forcing and contributes to warming. Conversely, if it reflects or scatters incoming solar radiation, negative radiative forcing occurs, producing a cooling effect. At the same time, the overall climatic effect is determined by

⁵⁴ European Commission. The European Green Deal. Brussels : European Commission, 2019.

⁵⁵ IPCC. *Climate Change 2023: Synthesis Report*. Geneva, 2023.

complex interactions among different groups of atmospheric constituents, their concentrations, atmospheric lifetimes, and spatial distribution patterns.

According to current IPCC estimates, anthropogenic activities have already caused an increase in global mean temperature of approximately 1.1°C compared with the pre-industrial period (1850–1900), with rising greenhouse gas concentrations being the primary driver of this process. However, short-lived climate pollutants (SLCPs), aerosols, and products of photochemical reactions also play a significant role in shaping the contemporary climate.

Greenhouse Gases as the Main Driver of Contemporary Global Warming

Greenhouse gases constitute the principal group of atmospheric components determining the current pattern of climate change. Their ability to absorb longwave infrared radiation emitted by the Earth's surface produces the natural greenhouse effect, without which the Earth's average temperature would be approximately 33°C lower. However, the sharp increase in the concentrations of these gases as a result of anthropogenic activities has disrupted the natural energy balance of the atmosphere.

Carbon dioxide (CO₂) makes the largest contribution to contemporary global warming. Its atmospheric concentration has increased from approximately 280 ppm during the pre-industrial period to more than 420 ppm in the twenty-first century. The main sources include fossil fuel combustion, cement production, land-use change, and deforestation. A distinctive feature of CO₂ is its long persistence in the atmosphere, with its climatic influence extending from decades to centuries.

Methane (CH₄) is the second most important greenhouse gas. Although its atmospheric concentration is substantially lower than that of CO₂, methane has a considerably greater global warming potential over the first decades following its emission. An important characteristic of methane is its involvement in the photochemical formation of tropospheric ozone, which enhances its indirect climatic effect.

Nitrous oxide (N₂O) is another important greenhouse gas, with its main sources including the application of nitrogen fertilizers, agricultural production, and certain industrial processes.

Fluorinated gases (HFCs, PFCs, SF₆, and others) constitute a separate group and are used in refrigeration equipment, the electrical industry, and the manufacture of specialized equipment. Their atmospheric concentrations remain relatively low; however, the global warming potential of some compounds within this group is thousands of times greater than that of carbon dioxide.

In addition to conventional greenhouse gases, increasing attention is being paid to short-lived climate pollutants, which remain in the atmosphere for periods ranging from several days to several decades but exert significant

effects on both the climate system and public health. This group includes black carbon, tropospheric ozone, methane, and certain organic aerosols.

A distinctive feature of these substances is that reducing their emissions can produce rapid benefits both for improving atmospheric air quality and for slowing the rate of global warming. For this reason, international organizations regard the control of SLCP emissions as one of the most effective approaches in contemporary climate policy⁵⁶.

Interactions Among Different Groups of Atmospheric Pollutants

The climatic effects of individual atmospheric pollutants cannot be considered in isolation. Under real atmospheric conditions, pollutants interact with one another, participate in photochemical reactions, modify aerosol properties, and influence cloud formation processes.

It is precisely the multicomponent nature of atmospheric processes that necessitates a comprehensive approach to assessing the impacts of different pollutants on the climate system. Contemporary climate models increasingly integrate atmospheric physics, chemistry, biogeochemical cycles, and socio-economic development scenarios, enabling more scientifically robust predictions of the consequences of different environmental policy options.

An analysis of contemporary research indicates that the climatic role of atmospheric pollutants is determined not only by the magnitude of their emissions but also by their physicochemical properties, atmospheric lifetime, and interactions with other components of the climate system. Whereas the traditional approach focused primarily on reducing CO₂ emissions, contemporary international practice is increasingly oriented towards the integrated management of different groups of pollutants. For Ukraine, this implies the need to integrate decarbonization policies with programmes aimed at improving atmospheric air quality, enhancing energy efficiency, modernizing industry, and adapting to climate change.

Aerosols as Regulators of the Earth's Radiative Balance and Climate System

Aerosols are among the most important atmospheric components influencing the current state of the climate system. Unlike greenhouse gases, which primarily alter the thermal balance by absorbing longwave radiation, aerosol particles interact simultaneously with both shortwave solar radiation and longwave thermal radiation. Their effects depend on particle size, chemical composition, shape, colour, concentration, and altitude in the atmosphere. This multifactorial nature makes the quantitative assessment of aerosol impacts on climate particularly complex and explains why aerosols remain one of the major sources of uncertainty in contemporary climate models.

⁵⁶ Jacob D. J. Introduction to Atmospheric Chemistry. Princeton: Princeton University Press, 1999. 266 p.

According to their origin, atmospheric aerosols are classified as natural or anthropogenic. Natural aerosols include sea-salt aerosols, desert dust, volcanic ash, biological particles, and products of naturally occurring fires. Anthropogenic aerosols are generated through fossil fuel combustion, industrial activities, transport, biomass burning, and agricultural production. In contemporary urbanized regions, anthropogenic sources account for a predominant share of fine particulate matter (PM_{2.5}), which has particularly significant impacts on both public health and climate processes⁵⁷.

A distinctive feature of aerosols is their ability to exert both cooling and warming effects on the atmosphere. Light-coloured particles, particularly sulfate aerosols, efficiently scatter incoming solar radiation back into space, thereby increasing the albedo of the atmosphere and the Earth's surface. This produces negative radiative forcing, which partially offsets the warming caused by the accumulation of greenhouse gases. Consequently, during the second half of the twentieth century, intensive industrial sulfate pollution to some extent masked the magnitude of global warming.

In contrast, black carbon has an exceptionally high capacity to absorb solar radiation. Once released into the atmosphere, black carbon particles rapidly heat up and transfer heat to the surrounding air, causing localized atmospheric warming. Furthermore, when deposited on snow or ice surfaces, black carbon substantially reduces surface albedo, thereby accelerating the melting of glaciers and seasonal snow cover. This mechanism is particularly pronounced in high-altitude regions and the Arctic, where even a relatively small reduction in surface reflectivity can result in a substantial increase in the absorption of solar energy.

The most extensively studied mechanism through which aerosols interact with the climate system is their direct effect on the atmospheric radiative balance. This effect involves changes in the amount of solar energy reaching the Earth's surface as a result of the scattering or absorption of radiation by aerosol particles.

Sulfate, nitrate, and certain organic aerosols have high reflective properties and produce a cooling effect. In contrast, black carbon actively absorbs solar energy, thereby warming the atmosphere and altering the vertical temperature distribution. Mineral dust occupies an intermediate position, as its radiative properties depend largely on its mineralogical composition and particle size.

The overall direct effect of aerosols is determined not only by their concentration but also by the relative proportions of different particle types. In

⁵⁷ World Health Organization. WHO Global Air Quality Guidelines: Particulate Matter (PM_{2.5} and PM₁₀), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. Geneva : WHO, 2021. 290 p.

industrial regions, the cooling effect of sulfate aerosols tends to predominate, whereas in areas characterized by intensive biomass burning and extensive use of diesel fuels, the contribution of black carbon becomes considerably more significant.

Equally important is the indirect effect of aerosols, which occurs through their involvement in cloud formation. Most atmospheric aerosols act as cloud condensation nuclei around which water vapour condenses to form cloud droplets. As the number of such nuclei increases, a greater number of smaller droplets are formed, enhancing cloud reflectivity and increasing the amount of incoming solar radiation reflected back into space.

In addition to modifying the optical properties of clouds, aerosols also influence cloud lifetime. Smaller droplets coalesce more slowly, which delays precipitation formation and prolongs the lifetime of cloud systems.

Through the combined effects of direct and indirect interactions, aerosols are capable of altering not only air temperature but also precipitation patterns, monsoon characteristics, cyclone trajectories, and even the frequency of certain extreme weather events⁵⁸.

Despite substantial advances in climate modelling, aerosols remain one of the major sources of uncertainty in projections of global climate change. The principal reasons include difficulties in determining their chemical composition, rapid transformation processes within the atmosphere, heterogeneous spatial distribution, and complex interactions with water vapour, clouds, and natural biogeochemical cycles.

The IPCC Sixth Assessment Report emphasizes that improving scientific understanding of aerosol processes is one of the key directions in the development of contemporary climatology. Particular attention is devoted to the integration of satellite observations, ground-based monitoring, and numerical atmospheric models, which makes it possible to reduce uncertainty in projections of future climate scenarios.

The analysis conducted indicates that aerosols act as distinctive “regulators” of the climate system, capable of both amplifying and mitigating the effects of global warming. Unlike greenhouse gases, their influence is not unidirectional and is determined by a complex combination of physical, chemical, and meteorological factors. Therefore, contemporary environmental policy cannot be based solely on reducing the concentrations of individual pollutants. It must take into account the complex interactions between aerosol particles and the climate system, the specific characteristics of regional atmospheric pollution, and the potential secondary effects of environmental protection measures⁵⁹.

⁵⁸ World Meteorological Organization. State of Global Air Quality and Climate. Geneva : WMO, 2024.

⁵⁹ IPCC. *Climate Change 2023: Synthesis Report*. Geneva, 2023.

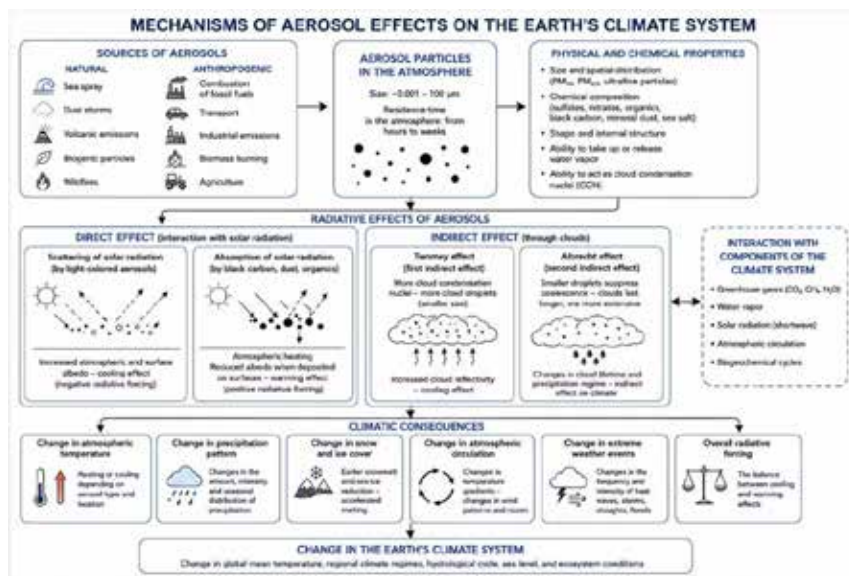


Fig. 2. Mechanisms of Aerosol Effects on the Earth's Climate System^{60, 61, 62}

Black Carbon as a Short-Lived Climate Pollutant

Among all atmospheric aerosols, black carbon (BC) occupies a particularly important position and is classified by contemporary international organizations as a short-lived climate pollutant (SLCP). Unlike most light-scattering aerosols, black carbon actively absorbs solar radiation, causing atmospheric warming and altering the atmospheric energy balance. According to estimates by the Intergovernmental Panel on Climate Change (IPCC), black carbon is among the most significant anthropogenic contributors to positive radiative forcing after carbon dioxide, although its atmospheric lifetime typically ranges from only a few days to approximately two weeks⁶³.

The main sources of black carbon include the incomplete combustion of fossil fuels, diesel engines, thermal power generation, residential heating with solid fuels, the burning of agricultural residues, wildfires, and other biomass combustion processes. In highly urbanized countries, road transport accounts for a substantial share of black carbon emissions, whereas in regions where

⁶⁰ Vallero D. A. Fundamentals of Air Pollution. 5th ed. Amsterdam : Elsevier, 2014. 996 p.

⁶¹ Jacob D. J. Introduction to Atmospheric Chemistry. Princeton : Princeton University Press, 1999. 266 p.

⁶² Möller D. Chemistry of the Climate System. Berlin; Boston : De Gruyter, 2014. 786 p.

⁶³ IPCC. *Climate Change 2023: Synthesis Report*. Geneva, 2023.

wood and coal are traditionally used for household purposes, residential and communal sources tend to predominate.

A distinctive feature of black carbon is its exceptionally high optical activity.

For Ukraine, the issue of black carbon has become particularly relevant in the context of the full-scale war. Large-scale fires resulting from hostilities, the destruction of industrial enterprises, oil depots, energy infrastructure facilities, and residential buildings are accompanied by significant emissions of incomplete combustion products, among which black carbon occupies a prominent place. In addition to directly deteriorating air quality, these emissions may potentially affect the regional radiation balance and climate processes, highlighting the need for their systematic monitoring and integration into post-war environmental recovery programs.

The analysis demonstrates that black carbon is a unique atmospheric pollutant that simultaneously acts as a toxic component of fine particulate matter and one of the most powerful short-lived climate forcers. Its impact extends far beyond local air pollution and manifests itself through changes in the radiation balance, snow-cover albedo, cloud microphysics, and regional atmospheric circulation. For Ukraine, particularly during the war and post-war periods, controlling black carbon emissions should become one of the priorities of environmental and climate policy, as it provides a dual benefit: rapid improvement in atmospheric air quality and a contribution to mitigating the effects of global climate change^{64, 65}.

Sulfate and Organic Aerosols as Drivers of Climate-System Cooling

Among atmospheric aerosols, sulfate and organic aerosols occupy a special place because, unlike black carbon, they predominantly produce negative radiative forcing and temporarily mitigate the effects of global warming. Their climatic effect is determined by their strong ability to scatter shortwave solar radiation, thereby increasing atmospheric albedo and reducing the amount of energy reaching the Earth's surface. Therefore, these aerosols are regarded as one of the natural and anthropogenic mechanisms that partially offset the warming caused by the accumulation of greenhouse gases.

Sulfate aerosols are formed primarily through the oxidation of sulfur dioxide (SO₂), which is released into the atmosphere during the combustion of coal, fuel oil, and petroleum products, as well as from metallurgical production and certain chemical processes. In addition to anthropogenic sources, volcanic eruptions make a significant contribution to the formation of sulfate aerosols.

⁶⁴ Моніторинг забруднення повітря на території України. URL: <https://www.saveecobot.com/maps/kharkiv>).

⁶⁵ Скок А., Хрутьба В. Якість атмосферного повітря в Україні до і під час повномасштабного вторгнення. Міжнародний фонд відродження. Київ, 2023. С. 5–24.

A distinctive feature of sulfate aerosols is their high efficiency in scattering solar radiation. They reflect part of the incoming energy back into space, thereby reducing the warming of the Earth's surface. According to IPCC estimates, sulfate aerosols provide the largest cooling contribution among anthropogenic aerosols. However, this effect is short-lived, since the average atmospheric lifetime of such particles is only a few days to several weeks⁶⁶.

Along with their direct radiative effect, sulfate aerosols significantly influence cloud formation processes. Due to their high hygroscopicity, they readily act as cloud condensation nuclei, increasing the number of small droplets in clouds. As a result, cloud reflectivity increases, cloud lifetime is prolonged, and the spatial distribution of precipitation is altered. According to IPCC assessments, this indirect effect through cloud modification remains one of the major sources of uncertainty in contemporary climate projections⁶⁷.

Organic aerosols constitute an extremely diverse group of atmospheric particles composed of hundreds of organic compounds of different origins. They are commonly divided into primary organic aerosols (POA), which are emitted directly into the atmosphere, and secondary organic aerosols (SOA), which are formed through photochemical reactions involving volatile organic compounds.

Sources of organic aerosols include transport, industry, biomass combustion, forest fires, agriculture, as well as natural biogenic processes. A significant proportion of secondary organic aerosols is formed through the oxidation of isoprene and monoterpenes emitted by vegetation. Thus, even natural ecosystems contribute to the formation of the background concentration of organic aerosols in the atmosphere.

The climatic effect of organic aerosols is more complex than that of sulfate aerosols. Most organic particles scatter solar radiation and thereby contribute to atmospheric cooling. At the same time, a specific group of organic aerosols, known as brown carbon, is capable of absorbing part of the incoming solar radiation, particularly in the ultraviolet and blue spectral ranges, thereby producing a localized warming effect. Therefore, the overall climatic impact of organic aerosols is determined by the balance between light-scattering and light-absorbing components⁶⁸.

Another important aspect is the interaction of organic aerosols with water vapor. Some organic compounds increase the hygroscopicity of aerosol particles, facilitating the formation of cloud droplets. Others, by contrast, reduce their

⁶⁶ IPCC. *Climate Change 2023: Synthesis Report*. Geneva, 2023.

⁶⁷ IPCC. *Climate Change 2023: Synthesis Report*. Geneva, 2023.

⁶⁸ Jacob D. J. *Introduction to Atmospheric Chemistry*. Princeton : Princeton University Press, 1999. 266 p.

ability to act as condensation nuclei, thereby altering cloud microphysics. This demonstrates the complex nature of interactions between organic matter and atmospheric processes and explains why its role in the climate system continues to be actively investigated.

One of the most important features of contemporary climate policy is the so-called aerosol paradox. Measures aimed at reducing emissions of sulfur dioxide and fine particulate aerosols undoubtedly improve atmospheric air quality and reduce morbidity and premature mortality among the population. However, at the same time, they diminish the cooling effect of atmospheric aerosols, which has partially offset the warming caused by greenhouse gases.

Therefore, contemporary international policy is increasingly focused on an integrated approach that involves the simultaneous reduction of greenhouse gas emissions, black carbon, and other atmospheric pollutants. Only such an integrated strategy can prevent undesirable climatic consequences and ensure the achievement of the objectives of the European Green Deal and the Paris Agreement^{69, 70}.

Climate Change as a Factor Contributing to the Deterioration of Atmospheric Air Quality

For a long time, atmospheric air pollution was regarded primarily as a driver of global climate change. However, contemporary research demonstrates the existence of a reverse cause-and-effect relationship: climate change itself is becoming an important factor in the transformation of the atmospheric environment and the deterioration of air quality. Therefore, in recent years, the concept of “Climate–Air Quality Feedback” has been increasingly used in the international scientific literature.

The increase in global mean temperature contributes to the intensification of photochemical reactions in the troposphere, resulting in enhanced formation of ground-level ozone and secondary organic aerosols. Rising temperatures also increase the evaporation and emission of volatile organic compounds from natural and anthropogenic sources, creating additional conditions conducive to the formation of photochemical smog.

At the same time, the increasing frequency of heat waves, droughts, large-scale forest fires, and dust storms is accompanied by a sharp increase in the concentrations of fine particulate matter (PM_{2.5}), black carbon, and toxic combustion products. Such phenomena are increasingly transboundary in nature and are capable of affecting air quality far beyond the regions in which they originate.

⁶⁹ European Commission. The European Green Deal. Brussels : European Commission, 2019.

⁷⁰ Paris Agreement. URL: <https://unfccc.int/process-and-meetings/the-paris-agreement>.

For Ukraine, risks associated with longer periods of drought, increased wildfire risk in natural ecosystems, degradation of soil cover, and changes in atmospheric circulation patterns are becoming particularly relevant. The combined effects of climate change, anthropogenic pressure, and the consequences of military hostilities create new challenges for environmental monitoring systems and atmospheric air quality management.

Thus, contemporary environmental policy should take into account the bidirectional nature of the interaction between climate change and atmospheric pollution, since the effectiveness of emission reduction measures directly depends on future climatic conditions.

Adaptation Strategies for Atmospheric Air Quality Management under Climate Change

Climate change adaptation is one of the key areas of contemporary environmental policy. Unlike climate change mitigation measures aimed at reducing anthropogenic emissions, adaptation strategies are designed to enhance the resilience of natural and socio-economic systems to climate transformations that have already become unavoidable.

In the field of atmospheric air protection, priority areas of adaptation include the development of integrated monitoring systems, modernization of automated observation station networks, widespread use of satellite-based Earth remote sensing technologies, implementation of mathematical forecasting models, and application of artificial intelligence algorithms for the rapid assessment of environmental risks.

Equally important are Nature-based Solutions, which involve expanding urban green spaces, creating ecological corridors, developing green roofs and vertical greening systems, restoring wetlands, and optimizing the spatial structure of urban areas. Such measures not only improve atmospheric air quality but also contribute to reducing urban temperatures, enhancing carbon dioxide sequestration, and increasing the resilience of urbanized areas to extreme weather events^{71, 72, 73}.

Of particular importance for Ukraine is the integration of climate policy into post-war recovery programs. The reconstruction of industry, transport infrastructure, housing, and the energy sector should be carried out in accordance with the principles of low-carbon development, resource efficiency, and the European Green Deal. Such an approach creates the prerequisites for simultaneously enhancing environmental security, improving atmospheric air quality, and strengthening the country's climate resilience.

⁷¹ European Commission. The European Green Deal. Brussels : European Commission, 2019.

⁷² Paris Agreement. URL: <https://unfccc.int/process-and-meetings/the-paris-agreement>.

⁷³ European Centre for Medium-Range Weather Forecasts. Copernicus Atmosphere Monitoring Service (CAMS): Global and Regional Air Quality Products. Reading: ECMWF, 2024.

The analysis has demonstrated that atmospheric pollution and global climate change are interdependent processes that form an integrated natural–anthropogenic system. Greenhouse gases, aerosols, short-lived climate pollutants, and secondary products of atmospheric chemistry affect the Earth's radiation balance in different ways; however, their cumulative effect is manifested in the transformation of climatic conditions, changes in atmospheric circulation patterns, and an increasing frequency of extreme natural events.

It has been established that climate change, in turn, exacerbates atmospheric air quality problems by intensifying photochemical processes, increasing the scale of wildfires and dust storms, and enhancing secondary aerosol formation. This confirms the existence of a persistent bidirectional relationship between atmospheric pollution and the climate system.

The transition to an integrated model of atmospheric air quality management that combines modern monitoring systems, mathematical modelling, geoinformation technologies, satellite observations, and artificial intelligence tools has been substantiated. Such an approach ensures the timely identification of environmental risks, enhances the effectiveness of environmental protection policies, and facilitates adaptation to climate change.

For Ukraine, the integration of environmental policy with post-war recovery and European integration processes is of particular importance. The implementation of the principles of low-carbon development, the digital transformation of environmental monitoring, and the introduction of Nature-based Solutions create the necessary prerequisites for ensuring environmental security, improving public health, and achieving the Sustainable Development Goals.

CONCLUSIONS

The study has demonstrated that atmospheric air pollution remains one of the most significant environmental problems of the present day, characterized by a pronounced global and transboundary nature and directly affecting public health, the functioning of natural ecosystems, and climate processes. Increasing anthropogenic pressure, urbanization, the development of industry, energy production and transport, the use of fossil fuels, as well as the growing frequency of natural and anthropogenic emergencies necessitate further improvement of atmospheric air protection mechanisms.

It has been established that the current structure of atmospheric pollution is shaped by both stationary and mobile sources, whose contributions vary considerably depending on the level of industrialization, the structure of the energy sector, transport intensity, and the natural and climatic characteristics of a particular area. Among the priority pollutants, particulate matter (PM_{2.5}

and PM₁₀), nitrogen and sulfur oxides, ground-level ozone, carbon monoxide, volatile organic compounds, heavy metals, and black carbon pose particular environmental hazards. A significant proportion of these components are characterized not only by their toxic effects on the human body but also by their ability to participate in complex physicochemical processes in the atmosphere.

The problem of fine particulate matter, particularly PM_{2.5} and PM₁₀, is of particular importance. The small size of these particles contributes to their prolonged residence in the atmosphere, long-range transport, and penetration into the human respiratory system. An analysis of global trends confirms that PM_{2.5} concentrations in a considerable number of countries and cities remain above the levels recommended by the World Health Organization. This necessitates strengthened control over sources of particulate matter emissions and the expansion of continuous monitoring networks.

Black carbon is an important component of atmospheric aerosols, combining the properties of an air pollutant and a short-lived climate forcer. Its formation is primarily associated with the incomplete combustion of fossil fuels and biomass. Reducing black carbon emissions can provide a dual benefit: improving atmospheric air quality and reducing the adverse anthropogenic impact on the climate system.

The study has also confirmed the close relationship between atmospheric air pollution and climate change. Rising temperatures, changes in atmospheric circulation patterns, droughts, heat waves, dust events, and the increasing scale of wildfires can contribute to the accumulation and transport of pollutants. At the same time, certain atmospheric components affect the Earth's radiation balance and climate processes. This substantiates the need to integrate air quality management policies with climate change mitigation and adaptation measures.

The analysis of the situation in Ukraine has revealed a substantial transformation in the structure of anthropogenic pressure on atmospheric air under the conditions of the full-scale war. Statistical data demonstrate an overall reduction in emissions compared with the pre-war period. However, this trend should not be interpreted unequivocally as an indication of improved environmental efficiency of the economy. To a considerable extent, it is associated with declining industrial production, the destruction or shutdown of enterprises, changes in the structure of energy consumption, the occupation of parts of the country's territory, and incomplete statistical reporting. At the same time, military hostilities have created new sources of pollution associated with fires, explosions, the destruction of industrial and energy infrastructure, and the use of autonomous energy supply systems.

It has been established that one of the key areas for improving atmospheric air protection is the modernization of the environmental monitoring system.

The traditional model, based predominantly on stationary observation stations, no longer fully meets the requirements of operational air quality management. An integrated model combining reference and automated monitoring stations, sensor networks, mobile measurement systems, satellite observations, geographic information systems, and mathematical modelling represents a promising approach.

For Ukraine, the modernization of the atmospheric air monitoring system should be carried out in accordance with European principles and standards, ensuring the compatibility of national information systems with European platforms and making extensive use of the capabilities provided by Copernicus and the Copernicus Atmosphere Monitoring Service (CAMS). Important prerequisites for the effectiveness of such a system include open access to environmental information, spatial expansion of the monitoring network, automation of data transmission, and ensuring data accessibility for public authorities, researchers, and the general public.

Thus, a prospective model of atmospheric air protection should be based on a comprehensive combination of emission reduction measures, the development of a modern monitoring system, the digitalization of environmental information, and the integration of climate and environmental protection policies. For Ukraine, the implementation of such an approach is particularly important in the context of European integration and post-war recovery. The reconstruction of industry, the energy sector, and transport infrastructure should be based on the principles of environmental modernization, decarbonization, and the application of modern emission control technologies.

The further development of automated and digital observation systems, the integration of ground-based and satellite data, and the application of geographic information technologies and artificial intelligence create the prerequisites for establishing a fundamentally new atmospheric air quality management system. Its implementation will contribute to the timely identification of environmental risks, improve the evidence base for management decisions, reduce the adverse effects of pollution on public health, and ensure the environmentally safe and sustainable development of Ukraine.

SUMMARY

The current state and key trends in atmospheric air pollution are investigated in the context of increasing anthropogenic pressure and global climate change. The main natural and anthropogenic sources of air pollution are systematized, and the environmental hazards associated with priority pollutants, including particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen and sulfur oxides, ground-level ozone, and black carbon, are characterized. The impacts of atmospheric

pollutants on public health, natural ecosystems, and climate processes are analyzed. Global and national trends in atmospheric air quality are examined, with particular attention to the transformation of anthropogenic pressures in Ukraine under wartime conditions. Contemporary approaches to atmospheric air monitoring are summarized, and the prospects for the application of automated monitoring stations, sensor networks, Earth remote sensing, and geographic information technologies are identified. Particular attention is given to the digitalization of monitoring and the application of Internet of Things (IoT), Big Data, machine learning, and artificial intelligence technologies for air quality analysis and forecasting. The need to establish an integrated atmospheric air monitoring system in Ukraine in accordance with contemporary European approaches and the objectives of environmentally sustainable post-war recovery is substantiated.

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