
MONITORING AND ASSESSMENT OF ATMOSPHERIC AIR QUALITY: SOURCES OF POLLUTION AND IMPACT ON ECOSYSTEMS

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DOI <https://doi.org/10.30525/978-9934-26-654-6-5>

INTRODUCTION

The current stage of society's development is characterized by an increase in anthropogenic pressure on the natural environment, which raises the issue of its preservation and rational use^{1, 2, 3}. Environmental challenges related to climate change, ecosystem degradation, and biodiversity loss are becoming global in nature and require comprehensive scientific understanding and effective management decisions at the national and international levels^{4, 5, 6}. One of the fundamental rights of Ukrainian citizens is the state-guaranteed right to an ecological environment that is safe for life and health, which is enshrined in national legislation and is part of constitutional human rights⁷.

¹ Anthropogenic modifications: impacts and conservation strategies / A. Belgrano, F. Cucchiella, D. Jiang, M. Rotilio. *Scientific reports*. 2023. Vol. 13, № 1. P. 12009. <https://doi.org/10.1038/s41598-023-38940-x>

² Analysis of anthropogenic impact on the environment, measures to reduce it, and waste management / N. A. Ereemeva, O. A. Savoskina, L. M. Poddymkina et al. *Frontiers in bioengineering and biotechnology*. 2023. Vol. 11. P. 1114422. <https://doi.org/10.3389/fbioe.2023.1114422>

³ Foysal M. J., Neilan B. A., Timms V. The impact of anthropogenic activities on antimicrobial and heavy metal resistance in aquatic environments. *Applied and environmental microbiology*. 2025. Vol. 91, № 4. P. e0231724. <https://doi.org/10.1128/aem.02317-24>

⁴ Wood Hansen O., van den Bergh J. Environmental problem shifting from climate change mitigation: A mapping review. *PNAS nexus*. 2023. Vol. 3, № 1. pgad448. <https://doi.org/10.1093/pnasnexus/pgad448>

⁵ Climate change, biodiversity loss, and Indigenous Peoples' health and wellbeing: a systematic umbrella review protocol / L. J. Brubacher, T. T. Chen, S. Longboat et al. *Systematic reviews*. 2024. Vol. 13, № 1. P. 8. <https://doi.org/10.1186/s13643-023-02423-x>

⁶ Interconnecting global threats: climate change, biodiversity loss, and infectious diseases. The Lancet / A. Pfenning-Butterworth, L. B. Buckley, J. M. Drake et al. *Planetary health*. 2024. Vol. 8, № 4. P. 270–283. [https://doi.org/10.1016/S2542-5196\(24\)00021-4](https://doi.org/10.1016/S2542-5196(24)00021-4)

⁷ Бузунко О. А. Функції держави із забезпечення судового захисту екологічних прав громадян. *Юридичний вісник*. 2021. № 1. С. 235–240. DOI <https://doi.org/10.32837/yuv.v0i1.2104>

Human interests, in particular the creation of safe living conditions, including the environmental component, are among Ukraine's key national interests^{8, 9}. The National Security Strategy of Ukraine emphasizes that personal security is the foundation of state security as a whole, and environmental security is one of its defining components^{10, 11, 12}.

The state provides guarantees for the creation of a safe environment, including an ecological one, for the life and health of the population, which is defined as one of the basic principles of environmental protection^{13, 14}. At the same time, the ecological environment is important not only for humans, but also for the existence and development of the animal world, as it represents a complex of natural conditions and factors that ensure the vital activity, reproduction, and evolutionary development of living organisms¹⁵.

The functioning of natural systems is based on a combination of various components and processes that are closely interrelated^{16, 17}. Within these systems, the environment for living organisms is formed, which determines the conditions of their life activity, adaptive capabilities, and the stability of ecological relationships. Thus, the ecological environment includes a set of physical, chemical, and biological factors, as well as a system

⁸ Buzunko O., Krasnova Y. Features of Judicial Protection of Environmental Rights of Citizens in the European Court of Human Rights. *Law. Human. Environmen.* 2022. Vol. 13, № 2. P. 7–16. doi:10.31548/law2022.02.001

⁹ Мельниченко О. А., Макарова В. І., Старусева В. В. Екологічна безпека: значення та взаємозв'язок з іншими складовими національної безпеки. *Національні інтереси Україн.* 2025. № 5 (10). С. 1164–1173. [https://doi.org/10.52058/3041-1793-2025-5\(10\)-1164-1173](https://doi.org/10.52058/3041-1793-2025-5(10)-1164-1173)

¹⁰ Заржицький О. С. Актуальні проблеми правового забезпечення екологічної політики України (теоретичні аспекти) : монографія. Дніпропетровськ : Національний гірничий університет, 2012. 200 с.

¹¹ Ващишин М. Я. Екологічне право vs право довкілля. *Юридичний науковий електронний журнал.* 2024. № 6. С. 171–175. DOI <https://doi.org/10.32782/2524-0374/2024-6/41>

¹² Ващенко С., Носаченко В. Державна політика у сфері екологічної безпеки. *Публічне управління: концепції, парадигма, розвиток, удосконалення.* 2024. № 7. С. 14–21. <https://doi.org/10.31470/2786-6246-2024-7-14-21>

¹³ Андрійко О. Ф., Кисіль Л. С. Адміністративно-правове забезпечення реалізації прав і свобод громадян в Україні. *Часопис Київського університету права.* 2015. № 3. С. 107–110.

¹⁴ Green infrastructure and relationship with urbanization – Importance and necessity of integrated governance / N. V. Miroshnyk, A. F. Lichanov, T. O. Grabovska et al. *Land Use Policy.* 2021 № 114. P. 105941. <https://doi.org/10.1016/j.landusepol.2021.105941>

¹⁵ Кондратьєва К. А. Актуальні дослідження у галузі правового регулювання екологічної безпеки в сільському господарстві. *Юридична Україна.* 2011. № 7. С. 37–41.

¹⁶ Krohs U., Zimmer M. Do ecosystems have functions?. *Ecology and evolution.* 2023. Vol. 13, № 9. P. e10458. <https://doi.org/10.1002/ece3.10458>

¹⁷ Regulation in ecological systems: an overview / C. M. Pinto Leite, Í. N. de Carvalho, J. G. D. E. Coutinho, C. N. El-Hani. *History and philosophy of the life sciences.* 2025. Vol. 47, № 4. P. 58. <https://doi.org/10.1007/s40656-025-00707-0>

of interactions between various components of the biocenosis—animals, plants, and microorganisms that form integral ecosystems¹⁸. Disruption of these interrelationships due to anthropogenic impact, climate change, or degradation of natural resources leads to a decrease in the stability of ecosystems and negatively affects their functioning. The quality and stability of the ecological environment determines not only the survival of individual species, but also the preservation of biodiversity as the basis for ecological balance and sustainable development of natural systems^{19, 20}. Thus, ensuring environmental security is a complex task of state policy that combines the interests of individuals, society, and the environment and is of strategic importance for the sustainable development of Ukraine.

The development of humanity is closely linked to the growth of industrial production, which is one of the key factors of economic progress, but at the same time is a source of increased anthropogenic pressure on the environment^{21,22}. Under conditions of industrialization and urbanization, the volume of pollutant emissions into the atmosphere tends to increase, leading to a deterioration in air quality. The main sources of atmospheric pollution remain industrial enterprises and motor transport^{23, 24, 25}, with industrial emissions accounting for almost twice as much as emissions from vehicles. The most intense volumes of pollutants enter the air as a result of the activities

¹⁸ Effect of organic farming on insect diversity / T. Grabovska, V. Lavrov, O. Rozputnii et al. *Ukrainian Journal of Ecology*. 2020. Vol. 10, № 4. 96–101. doi 10.15421/2020_174

¹⁹ Гетьман А. П. Верховенство права в інституті управління природокористуванням та охороною довкілля. *Екологічне право України. Науково-практичний журнал*. 2017. № 3-4. С. 2–7.

²⁰ Святченко Л. О., Корабльова А. А. Поняття та юридичні ознаки екологічної безпеки у тваринництві. *Право. Людина. Довкілля. К. : НУБіП України*. 2019. Том 10, № 1. С. 73–82. <https://doi.org/10.31548/law2019.01.010>

²¹ Analysis of anthropogenic impact on the environment, measures to reduce it, and waste management / N. A. Ereemeeva, O. A. Savoskina, L. M. Poddymkina et al. *Frontiers in bioengineering and biotechnology*. 2023. Vol. 1. P. 1114422. <https://doi.org/10.3389/fbioe.2023.1114422>

²² Rhind S. M. Anthropogenic pollutants: a threat to ecosystem sustainability?. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*. 2009. Vol. 364, № 1534. P. 3391–3401. <https://doi.org/10.1098/rstb.2009.0122>

²³ Chandrappa R., Chandra Kulshrestha U. Major Issues of Air Pollution. *Sustainable Air Pollution Management: Theory and Practice*. 2015. P. 1–48. https://doi.org/10.1007/978-3-319-21596-9_1

²⁴ Anthropogenic modifications: impacts and conservation strategies / A. Belgrano, F. Cucchiella, D. Jiang, M. Rotilio. *Scientific reports*. 2023. Vol. 13, № 1. 12009. <https://doi.org/10.1038/s41598-023-38940-x>

²⁵ Effects of transport-carbon intensity, transportation, and economic complexity on environmental and health expenditures / Z. Hussain, B. Marcel, A. Majeed, R. S. M. Tsimisaraka. *Environment, development and sustainability*, 2023. P. 1–31. Advance online publication. <https://doi.org/10.1007/s10668-023-03297-8>

of thermal power plants that use fossil fuels and are characterized by high emissions of sulfur, nitrogen, carbon, and particulate matter.

A significant contribution to atmospheric pollution is made by metallurgical and coal industry enterprises, whose operations are accompanied by intensive emissions of toxic gaseous compounds, heavy metals, and dust fractions of varying dispersibility. Such pollutants can accumulate in the air, soil, and water bodies for a long time, leading to the deterioration of the natural environment and increased environmental risks for the population, in particular an increase in the incidence of respiratory and cardiovascular diseases^{26, 27}. Given the preservation of traditional production processes, these industries remain among the most environmentally burdensome. In this regard, it is particularly important to introduce modern environmentally friendly and resource-saving technologies, gradually modernize production processes, improve the efficiency of gas cleaning facilities, and strengthen state and public control over compliance with industrial emission standards. The implementation of such measures is a necessary prerequisite for reducing the anthropogenic load on the atmosphere and ensuring the environmental safety of regions.

The state of atmospheric air and the natural environment as a whole is influenced by a complex of interrelated natural and anthropogenic factors, among which military emergencies occupy a special place^{28, 29, 30}. Combat operations are accompanied by large-scale destruction of industrial, transport, and energy infrastructure, leading to a sharp increase in emissions of pollutants into the atmosphere, as well as secondary pollution of soil and water bodies³¹.

According to available estimates, the environmental damage caused to Ukraine's environment, in monetary terms, amounted to approximately

²⁶ Belokon K. V. The investigation of the emissions influence from industrial enterprises on pollution of atmospheric air in the zavodskiy district of Zaporizhzhya. *Collection of scholarly papers of Dniprovsk State Technical University (Technical Sciences)*. 2018. Vol. 2, № 33. P. 91–96. <https://doi.org/10.31319/2519-2884.33.2018.206>

²⁷ Osokina N. Modern problems of Ukraine's ecology: agricultural pollutants and the quality of drinking water in the city of Kyiv. *Environmental safety and environmental management*. 2024. Vol. 3, № 51. P. 22–27. <https://doi.org/10.32347/2411-4049.2024.3.22-27>

²⁸ Leaning J. Environment and health: 5. Impact of war. *CMAJ : Canadian Medical Association journal = journal de l'Association medicale canadienne*. 2000. Vol. 163, № 9. P. 1157–1161.

²⁹ Ivanet M., Hordienko A., Horielyshev S. Analysis of sources of military emergencies and their consequences. *Honor and law*. 2023. Vol. 1 (84). P. 36–43. DOI: <https://doi.org/10.33405/2078-7480/2023/1/84/276810>

³⁰ Environmental consequences of military operations in Ukraine on the example of soil research in the Kharkiv region / O. V. Krainiuk, Y. V. Buts, R. V. Ponomarenko et al. *Journal of Geology, Geography and Geoecology*. 2025. Vol. 34, № 2. P. 304–317. <https://doi.org/10.15421/112526>

³¹ Безсонов С. Вплив «шуму війни» на екосистеми України. *Екологічний вісник*. [Електронний ресурс]. 2022. № 3. С. 25–26.

UAH 2 trillion as of December 2023, which indicates an unprecedented scale of negative impact on natural systems³². Back in 2015, as a result of intensive pollution of water resources and atmospheric air in the Donetsk region, signs of a potential environmental disaster were recorded, the risks of which have significantly increased in the context of further military escalation³³.

Natural reserves are particularly affected, especially in the Luhansk and Donetsk regions, where military operations are disrupting natural landscapes, destroying rare species of flora and fauna, and causing the loss of unique ecosystem functions³⁴. In just a year and a half of active warfare, an extremely large number of animals and plants have been destroyed, leading to a significant reduction in biodiversity and disruption of food chains^{35, 36, 37, 38}.

The impact of the war in Ukraine extends beyond national borders and has global environmental consequences^{39, 40, 41, 42}. Significant emissions of greenhouse gases and toxic substances into the atmosphere contribute to the

³² Стрілець П. Шкода довкілля. (2024). URL: <https://armyinform.com.ua/2023/04/15/shkoda-dovkil-lyu-vid-vijny-vzhe-perevyshhuje-19-tryljona-gryven-ruslan-strilecz/> (дата звернення: 14.01.2026).

³³ Війна і довкілля: заповідники в зоні АТО. Українська правда. URL: <https://life.pravda.com.ua/society/2015/03/7/190398/> (дата звернення: 14.01.2026).

³⁴ Губарева В. 500 днів війни: експерти обговорюють вплив війни на довкілля. URL: <https://uwecworkgroup.info/uk/500-days-of-war-experts-discuss-the-wars-environmental-impacts/> (дата звернення: 14.01.2026).

³⁵ Омельчук О, Садогурська С. Природа та війна: як військове вторгнення Росії впливає на довкілля України. URL: <https://ecoaction.org.ua/pryroda-ta-vijna.html> (дата звернення: 15.01.2026)

³⁶ Pirgo O. International and domestic practices for the protection of animals from cruelty in the conditions of armed conflict. *Bulletin of Luhansk Scientific-Educational Institute named after E. O. Didorenko*. 2024. Vol. 3. P. 125–133. <https://doi.org/10.32782/2786-9156.107.3.125-133>

³⁷ Dukhnevych A. V., Karpinska N. V. Environmental consequences of war: assessment of waste impact on the environment. *Analytical and Comparative Jurisprudence*. 2025. No. 1. С. 347–352. <https://doi.org/10.24144/2788-6018.2025.01.55>

³⁸ Бондар О. І., Фінін Г. С., Шевченко Р. Ю. Екологічні виклики воєнного часу: оцінка впливу на довкілля космічними системами дистанційного зондування та GPS-навігації. *Екологічні науки*. 2022. № 4 (43). С. 40–49. DOI: <https://doi.org/10.32846/2306-9716/2022.eco.4-43.7>

³⁹ Лісова Н. О. Вплив військових дій в Україні на екологічний стан території. *Наукові записки Тернопільського національного педагогічного університету імені Володимира Гнатюка. Серія: географія*. 2017. № 43 (2). С. 165–173.

⁴⁰ Екологічна безпека в умовах воєнного стану / О. М. Семерня, О. І. Любинський, І. В. Федорчук та ін. *Економічні науки: науково-практичний журнал*. 2022. № 2 (41). С. 62–66. <https://doi.org/10.32846/2306-9716/2022.eco.2-41.11>

⁴¹ Перспективи відшкодування екологічної шкоди, спричиненої збройною агресією РФ в рамках міжнародних екологічних угод: посібник / Є. Алексеева, С. Баран, С. Гольфстрём та ін. за наук. ред. О. Кравченко, Д. Скрильнікова. Львів : Видавництво «Компанія «Манускрипт»», 2023. 92 с.

⁴² Іванюга С., Якушенко Л. Пріоритети забезпечення екологічної безпеки України в умовах російської воєнної агресії : аналітична доповідь. *НІСД*. 2024. 61. <https://doi.org/10.53679/NISS-analytrep.2024.11>

acceleration of climate change, while pollution of surface and groundwater, soil degradation, and biodiversity loss threaten the stability of ecosystems not only at the regional but also at the planetary level^{43, 44}.

The southern regions of Ukraine are particularly vulnerable, where steppe ecosystems, due to their natural sensitivity to wind erosion, are undergoing accelerated degradation as a result of the destruction of vegetation cover and disruption of soil structure⁴⁵. In addition, the ecological balance in ornithological complexes is disrupted: intense noise and technogenic influences change bird behavior, causing the loss of traditional nesting sites and migration routes, which in turn leads to a decrease in population size and a reduction in the reproductive potential of species⁴⁶. Thus, military actions are a powerful destructive factor that has a complex impact on the atmosphere, biodiversity, and functioning of ecosystems, highlighting the need for scientific monitoring, post-war ecological rehabilitation, and integration of the ecological component into the national security system.

Thus, the state of atmospheric air and the natural environment in Ukraine is shaped by a combination of industrial, transport, and military factors, the effects of which are long-term and often irreversible. Ensuring environmental safety should be considered an integral part of national security and sustainable development of the state in the context of modern challenges.

1. The condition of the air basin as an indicator of environmental quality

Ensuring environmental safety and preventing negative changes in the natural environment is one of the priorities of the state environmental policy. To this end, Ukraine has a State Environmental Monitoring System in place, which provides for comprehensive and systematic observation of the state of key natural components, assessment of environmental risks, and forecasting of possible changes under the influence of natural and anthropogenic factors (Polozhennia

⁴³ The human toll and humanitarian crisis of the Russia-Ukraine war: The first 162 days / U. Haque, A. Naeem, S. Wang et al. *BMJ Global Health*. 2022. Vol. 7, № 9. article number e009550. <https://doi.org/10.1136/bmjgh-2022-009550>.

⁴⁴ Екологічні проблеми сільського господарства в умовах воєнного стану / О. Ф. Дунаєвська, І. М. Сокульський, Н. В. Мельник, А. О. Піщіль. *Екологічні науки*. 2024. № 1 (52). Том 1. С. 22–27. <https://doi.org/10.32846/2306-9716/2024.eco.1-52.1.3>

⁴⁵ Impact of the full-scale war in Ukraine on the environment: Environmental damage assessment / Yu., Polukarov, N., Kachynska, O., Polukarov et al. *Law. Human. Environment*. 2024. Vol. 15, № 1. P. 85–100. <https://doi.org/10.31548/law/1.2024.85>.

⁴⁶ Pipia S. The Effect of Russia's Invasion of Ukraine on Non-Human Animals: International Humanitarian Law Perspectives. *Israel Law Review*. 2024. Vol. 57, № 2. P. 265–287. <https://doi.org/10.1017/S0021223724000086>

pro derzhavnu systemu monitorynhu dovkillia : Postanova KМУ № 391, 1998)⁴⁷. Despite the existence of a regulatory framework and environmental control tools, atmospheric air remains one of the most vulnerable components of the environment. It is constantly polluted by stationary and mobile sources, accompanied by the release of a wide range of harmful impurities into the air. Some of these have a pronounced toxic and carcinogenic effect, posing a threat to public health and increasing the risk of premature mortality.

Particular attention is paid in global practice to assessing the impact of the most dangerous atmospheric pollutants. According to the recommendations of the World Health Organization, priority air quality indicators include ground-level ozone, particulate matter with an aerodynamic diameter of less than 2.5 µm, and nitrogen dioxide, which are characterized by a high risk of adverse effects on human health and require constant monitoring (nakaz Ministerstva okhorony zdorovia Ukrainy № 89 vid 17 sichnia 2022)⁴⁸.

A separate area of environmental assessment is the identification and classification of carcinogenic substances that can enter the atmosphere and pose a potential health risk to the population. The International Agency for Research on Cancer, in collaboration with the Ministry of Health of Ukraine, has compiled a list of such compounds and divided them into five groups depending on the degree of carcinogenic hazard (nakaz MOZ Ukrainy vid 20.06.2022 № 1054., 2024)⁴⁹. The introduction of this classification makes it possible to assess the risks of pollutants more reasonably, identify priority areas for environmental control, and develop effective preventive measures.

In addition, in the context of growing man-made and military risks, the use of specialized methods for predicting the likely impact of toxic substances in the event of accidents or emergencies is of particular importance (nakaz Ministerstva vnutrishnikh sprav Ukrainy № 1000 vid 29.11.2019)⁵⁰.

⁴⁷ Положення про державну систему моніторингу довкілля : Постанова КМУ № 391, 1998. URL: <https://zakon.rada.gov.ua/laws/show/391-98-%D0%BF#Text> (дата звернення: 15.01.2026).

⁴⁸ Оцінка ризику для здоров'я населення від забруднення атмосферного повітря: наказ Міністерства охорони здоров'я України № 89 від 17 січня 2022 р. URL: <https://moz.gov.ua/uk/decrees/nakaz-moz-ukraini-vid-17012022--89-pro-zatverdzhennja-metodichnih--rekomendacij-ocinka-riziku-dlja--zdorovja-naselennja-vid-zabrudnennja-atmosferного-povitlja> (дата звернення: 15.01.2026).

⁴⁹ Про затвердження Гігієнічного нормативу «Перелік речовин, продуктів, виробничих процесів, побутових та природних факторів, канцерогенних для людини» : наказ МОЗ України від 20.06.2022 № 1054. URL: <https://zakon.rada.gov.ua/laws/show/z0910-22#Text>. (дата звернення: 15.01.2026).

⁵⁰ Про затвердження Методики прогнозування наслідків виливу (викиду) небезпечних хімічних речовин під час аварій на хімічно небезпечних об'єктах і транспорті: наказ Міністерства внутрішніх справ України № 1000 від 29.11.2019 р. URL: <https://zakon.rada.gov.ua/laws/show/z0440-20#Text>. (дата звернення: 15.01.2026).

Such approaches allow for timely assessment of the scale of possible pollution, minimization of negative environmental impacts, and ensuring an adequate level of protection for the population. In this context, the state of atmospheric air is of particular importance as an integral indicator of the ecological quality of the environment, reflecting the cumulative impact of natural and anthropogenic factors and the level of technogenic load on the territory.

The current state of the environment is determined by the interaction of natural and anthropogenic factors, among which the state of atmospheric air is of particular importance. Air quality directly affects the health of the population, the functioning of ecosystems, and the stability of natural processes, therefore its systematic study is an important task of environmental science and natural resource management.

Research on the selected topic was conducted during 2023–2024 to assess the ecological state of the region's air basin and identify the main factors of its pollution. The object of the study is the ecological state of the air basin of the Zhytomyr region, while the subject is air quality indicators, sources of pollution, and their dynamics during the study period.

Various scientific methods were used to achieve the set goal. Among them are:

- analytical and generalisation – review of literary sources, processing of previous research results, formulation of conclusions;

- descriptive – systematisation and analysis of atmospheric air measurement results;

- comparative – comparison of the data obtained with the results of previous studies to identify trends and changes;

- cartographic – depiction of the spatial distribution of pollutants on a map of the region;

- statistical and graphical – processing of numerical data, construction of diagrams, graphs, and tables for visual presentation of results.

For direct research into the state of atmospheric air, air samples were taken using specialized instruments and impurities were determined in accordance with methodological recommendations and standards^{51, 52}. This comprehensive approach allows for a scientifically sound assessment of the state of the air basin and identification of key factors affecting its quality.

Emissions of pollutants into the atmosphere are mixtures or individual components that negatively affect air quality and the environment. Such substances are produced in certain facilities called emission sources and may

⁵¹ Методи вимірювання параметрів навколишнього середовища: підручник / Г. І. Гринь, В. І. Мошонько, О. В. Суворін та ін. Северодонецьк : Видавництво СНУ ім. В. Даля, 2019. 420 с.

⁵² 52. ДСТУ ISO 4219:2004. Якість повітря. Визначання газоподібних сірчистих сполук у навколишньому повітрі. Устаткування для відбирання проб (ISO 4219:1979, IDT).

be of chemical or biological origin. Pollutant emissions directly affect human health, ecosystems, and natural processes, so their regulation is an important element of state environmental policy.

In Ukraine, the list of pollutants and emission standards are approved by legislative and regulatory documents. In particular, these are Resolution of the Cabinet of Ministers of Ukraine No. 1598 of November 29, 2001, “List of the most common and dangerous pollutants, whose emissions into the atmosphere are subject to regulation” and Order of the Ministry of Ecology and Natural Resources No. 177 of May 10, 2002, “Instructions on the procedure and criteria for state registration of objects that have or may have a harmful effect on human health and the state of the atmosphere”. These documents establish which sources are subject to control and define the procedures for recording harmful emissions.

Emission standards are set for each pollutant, which allows for the assessment of the environmental impact of industrial and other enterprises. If the established standards are exceeded, the excess emissions are calculated and the amount of compensation for the damage caused is determined in accordance with the “Methodology for calculating the amount of compensation for damage caused to the state as a result of excess emissions of pollutants into the atmosphere”, approved by Order of the Ministry of Energy and Environmental Protection of Ukraine No. 277 of April 28, 2020. This approach not only allows for the assessment of economic damage, but also encourages enterprises to reduce emissions.

Separate procedures are provided for emergencies or martial law. For such cases, a methodology has been approved for determining unorganized emissions of pollutants into the air and calculating the amount of damage caused, in accordance with Order No. 175 of the Ministry of Environmental Protection and Natural Resources of Ukraine dated April 13, 2022. This allows for the rapid assessment of environmental damage in cases of emergencies and the planning of measures to minimize negative consequences.

An important indicator of atmospheric air quality is the calculation of pollutant emissions per person per year. This indicator is determined for stationary sources of pollution and used to assess long-term trends. An analysis of the dynamics shows that, compared to 2010, per capita emissions have almost halved, which is explained by the modernization of industrial enterprises, a reduction in production, and the introduction of modern purification technologies (Fig. 1). However, despite the positive trends, the problem of air pollution remains relevant and requires constant monitoring, the introduction of new environmental standards, and active state and public monitoring.

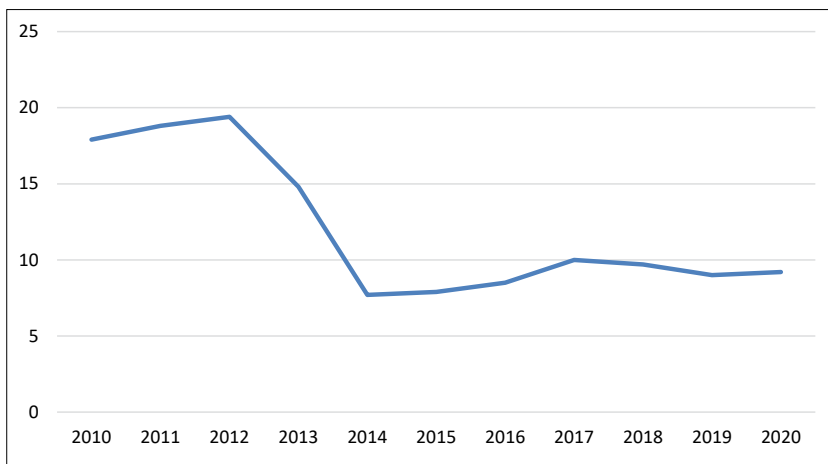


Fig. 1. Trends in emissions from stationary sources for the period 2010–2020 (kg/person)

In addition, it should be noted that modern approaches to emissions management include not only control over the amount of harmful substances, but also assessment of their impact on public health and ecosystems, forecasting possible consequences, and developing preventive measures. Including such measures in strategic environmental policy planning makes it possible to more effectively reduce anthropogenic pressure on the atmosphere and improve the quality of the environment at the regional and national levels.

Zhytomyr Oblast is an administrative-territorial unit comprising four districts and 66 territorial communities, among which the city of regional significance, Zhytomyr, is of particular importance. The region is located within two soil and climatic zones – Polissya and forest-steppe – which determines the diversity of natural conditions and influences the formation of the local climate. Typical meteorological phenomena are observed in the region’s atmosphere, including fog, wind, thunderstorms, and precipitation. In recent years, there has been an increase in the frequency and intensity of dangerous meteorological phenomena, including heavy rain and snowfall, strong winds, and squalls, which have a potentially negative impact on the natural environment and the socio-economic sphere.

Atmospheric air is a unique natural resource on which the life of all organisms on Earth depends. Ensuring its purity and sustainable condition is a pressing task for modern society and one of the priorities of the

state's environmental policy. Industrial development, intensive use of natural resources, and urbanization create an additional burden on the environment, which manifests itself, in particular, in an increase in the volume of pollutant emissions into the atmosphere and changes in the chemical composition of the air basin.

Monitoring the state of atmospheric air is an integral part of the environmental monitoring system, as it allows assessing the level of pollution and its impact on public health, ecosystems, and biodiversity⁵³. Despite this, in some cases, state air monitoring does not provide sufficient efficiency and completeness of data for comprehensive environmental management, planning of preventive measures, and response to emergencies. Harmful impurities are constantly entering the atmosphere along with emissions from industrial, transport, and domestic sources^{54, 55, 56}.

The main components of atmospheric air are nitrogen and oxygen, the latter accounting for approximately 21 percent by volume. In addition, air contains other gases, including argon, carbon dioxide, hydrogen, and water vapor, as well as various impurities^{57, 58, 59}. Impurities are variable components and depend on geographical location, type of human activity, seasonal and meteorological conditions. These include, in particular, ammonia, ozone,

⁵³ Федонюк М. А. До питання удосконалення системи державного екологічного моніторингу стану атмосферного повітря. *Електронний журнал «Державне управління: удосконалення та розвиток»*. 2013. № 2. <http://www.dy.nayka.com.ua/?op=1&z=541>

⁵⁴ Оцінка екологічного впливу нафтопереробного підприємства на навколишнє середовище України / С. В. Бойченко, О. Г. Пузік, П. І. Топільницький та ін. *Енергетика: економіка, технології, екологія*. 2016. № 4. С. 109–122.

⁵⁵ Петринич В. В., Л. І. Власик Петринич О. А. Свинець: токсикологічні, гігієнічні та біологічні аспекти. *Клінічна та експериментальна патологія*. 2017. Vol. 16, № 2. С. 97–102. <https://doi.org/10.24061/1727-4338.XVI.2.60.2017.20>

⁵⁶ Improvement of the current system for atmospheric air quality monitoring in Kyiv according to the EU requirements / I. V. Dvoretzka, M. V. Savenets, L. M. Nadochii et al. *Hydrology, Hydrochemistry and Hydroecology*. 2022. Vol. 3, № 65. P. 105–106. DOI: doi.org/10.17721/2306-5680.2022.3.8

⁵⁷ Jones R. L., Ball S. M., Shallcross D. E. Small scale structure in the atmosphere: implications for chemical composition and observational methods. *Faraday discussions*. 2005. Vol. 130. P. 165–524. <https://doi.org/10.1039/b502633b>

⁵⁸ McNeill V. F. Atmospheric Aerosols: Clouds, Chemistry, and Climate. *Annual review of chemical and biomolecular engineering*. 2017. Vol. 8. P. 427–444. <https://doi.org/10.1146/annurev-chembioeng-060816-101538>

⁵⁹ Schlesinger W. H., Bernhardt E. S. The Atmosphere. *Biogeochemistry*. 2020. P. 51–97. <https://doi.org/10.1016/B978-0-12-814608-8.00003-7>

sulfur oxides, methane, and other harmful substances^{60, 61, 62, 63}. It is these impurities that have the most significant impact on air quality and the ecological state of the region.

Air is an integral part of the natural environment and an important resource for human life and ecosystem development^{64, 65}. Its physical and chemical properties determine climatic conditions, environmental quality, and the functioning of natural processes, so assessing the state of atmospheric air and its components is a pressing task for environmental science.

The atmosphere is a complex gaseous envelope of the Earth, which forms a constant and stable complex of gases with a certain ratio of components, providing protection for the planet from cosmic radiation, maintaining temperature conditions, and enabling the existence of life^{66, 67}. The main gases in the atmosphere include nitrogen, oxygen, argon, carbon dioxide, water vapor, and other impurities that constantly circulate and interact with each other, affecting meteorological phenomena and the ecological state of regions.

Sanitary norms and standards are applied to preserve air quality and prevent pollution. Air quality is constantly monitored at the global level, which allows assessing its safety for human health and the environment. For example, in European countries, an air quality index is calculated every hour,

⁶⁰ Direct measurements of the convective recycling of the upper troposphere / P. O. Wennberg, E. Scheuer, J. Dibb et al. *Science (New York, N. Y.)*. 2007. Vol. 315, № 5813. P. 816–820. <https://doi.org/10.1126/science.1134548>

⁶¹ Changes in air quality and tropospheric composition due to depletion of stratospheric ozone and interactions with climate / X. Tang, S. R. Wilson, K. R. Solomon et al. *Photochemical & photobiological sciences : Official journal of the European Photochemistry Association and the European Society for Photobiology*. 2011. Vol. 10, № 2. P. 280–291. <https://doi.org/10.1039/c0pp90039g>

⁶² Active atmosphere-ecosystem exchange of the vast majority of detected volatile organic compounds / J. H. Park, A. H. Goldstein, J. Timkovsky et al. *Science (New York, N. Y.)*. 2013. Vol. 341 (6146). P. 643–647. <https://doi.org/10.1126/science.1235053>

⁶³ Volatile chemical products emerging as largest petrochemical source of urban organic emissions / B. C. McDonald, J. A. de Gouw, J. B. Gilman et al. *Science (New York, N. Y.)*, Vol. 359 (6377). P. 760–764. <https://doi.org/10.1126/science.aaq0524>

⁶⁴ Updates in Air Pollution: Current Research and Future Challenges / D. Vilcins, R. C. Christoferson, J. H. Yoon et al. *Annals of global health*. 2024. Vol. 90, № 1. P. 9. <https://doi.org/10.5334/aogh.4363>

⁶⁵ Environmental and Health Impacts of Air Pollution: A Review / I. Manisalidis, E. Stavropoulou, A. Stavropoulos, E. Bezirtzoglou. *Frontiers in public health*. 2020. Vol. 8. P. 14. <https://doi.org/10.3389/fpubh.2020.00014>

⁶⁶ Zahnle K., Schaefer L., Fegley B. Earth's earliest atmospheres. *Cold Spring Harbor perspectives in biology*. 2010. Vol. 2, № 10. a004895. <https://doi.org/10.1101/cshperspect.a004895>

⁶⁷ Experimental and simulation study of inert gas mixture inhibiting coal spontaneous combustion / X. Wang, L. Wang, W. Li, D. Liu. *Scientific Reports*. 2024. Vol. 14, 4305. <https://doi.org/10.1038/s41598-024-53979-0>

allowing for a rapid response to exceedances of permissible concentrations of harmful substances^{68, 69, 70}. According to international studies, less than 1 % of the world's population has access to clean, breathable air.

Effective management of atmospheric air quality requires the implementation of comprehensive measures. These include the development and implementation of programs to reduce pollution levels, compliance with environmental standards, assessment of the impact of new substances and compounds for which maximum permissible concentrations (MPC) have not yet been determined, as well as updating and improving national environmental standards. Equally important are international cooperation, consultation, protection of citizens' rights, and consideration of environmental aspects in land-use planning, enterprise modernization, and the implementation of preventive measures^{71, 72}.

All facilities that could potentially cause harmful emissions into the atmosphere and negatively affect public health are subject to state registration in accordance with the "Instructions on the procedure and criteria for state registration of facilities that have or may have a harmful effect on human health and atmospheric air quality" (Order of the Ministry of Ecology and Natural Resources of Ukraine No. 177 of May 10, 2002). Such registration ensures systematic control, the ability to assess risks to the environment and people, and the formation of scientifically based recommendations for regulating emissions and improving air quality.

Air quality is one of the key indicators of the ecological state of the natural environment and the level of safety of human life^{73, 74}. Air pollution

⁶⁸ Specific approach for continuous air quality monitoring / P. Zivkovic, M. A. Tomic, G. S. Ilic et al. *Hemijaska industrija*. 2012. Vol. 66, № 1. P. 85–93. <https://doi.org/10.2298/HEMIND110525066Z>

⁶⁹ Long-term, continuous air quality monitoring in a cross-sectional study of three UK non-domestic buildings / S., Stamp, E., Burman, C., Shrubsole et al. . *Building and Environment*. 2020. Vol. 180, № 24. 107071 doi.org/10.1016/j.buildenv.2020.107071

⁷⁰ Air quality monitoring using statistical learning models for sustainable environment / M. Imam, S. Adam, S. Dev, N. Nesa. *Intelligent Systems with Applications*. 2024. Vol. 22. 200333 <https://doi.org/10.1016/j.iswa.2024.200333>

⁷¹ Кожура Л. О. Адміністративно-правовий захист та охорона: поняття та співвідношення. *Науковий вісник Ужгородського національного університету. Серія «Право»*. 2015. Вип. 35. Ч. 1. Т. 2. С. 119–122.

⁷² Рубцова І. Поняття й особливості детермінанти «Охорона атмосферного повітря». *Екологічне право*. 2021. № 6. С. 107–110. <https://doi.org/10.32849/2663-5313/2021.6.17>

⁷³ Revised analyses of the National Morbidity, Mortality, and Air Pollution Study: mortality among residents of 90 cities / F. Dominici, A. McDermott, M. Daniels et al. *Journal of toxicology and environmental health. Part A*. 2005. Vol. 68 (13-14). P. 1071–1092. <https://doi.org/10.1080/15287390590935932>

⁷⁴ Air Pollution and Health: The Need for a Medical Reading of Environmental Monitoring Data / M., Iriti, P., Piscitelli, E., Missoni, A. Miani. *International journal of environmental research and public health*. 2020. Vol. 17, № 7. 2174. <https://doi.org/10.3390/ijerph17072174>

is both local and transboundary in nature, causing negative impacts on human health, the functioning of natural and anthropogenically transformed ecosystems, and the course of climatic processes. Prolonged exposure to elevated concentrations of pollutants is associated with an increased risk of respiratory, cardiovascular, and other chronic diseases, as well as a decrease in the resistance of biological systems to external stressors. In this regard, systematic monitoring of atmospheric air quality, identification and assessment of pollution sources, analysis of the spatial and temporal dynamics of emissions, and implementation of effective environmental monitoring systems are of particular importance. The data obtained through such monitoring provides a scientific basis for making management decisions in the field of environmental protection, developing preventive measures to reduce anthropogenic pressure, and forming environmentally oriented policies for sustainable development of territories.

Ukraine has approved a list of the most common and potentially dangerous pollutants, the emissions of which into the atmosphere are subject to state regulation. This is provided for by Resolution of the Cabinet of Ministers of Ukraine No. 1598 of November 29, 2001, “On Approval of the List of the Most Common and Dangerous Pollutants, the Emissions of Which into the Atmosphere are Subject to Regulation”. This list includes both common pollutants – nitrogen oxides, carbon monoxide, lead and its compounds, formaldehyde, as well as more dangerous substances, including metals, chlorine, fluorine, cyanides, freons, and other chemical compounds that can have a significant negative impact on the atmosphere and human health.

At the regional level, a list of enterprises whose activities are classified as environmentally hazardous due to emissions into the atmosphere has also been approved. Among them, the following stand out in the Zhytomyr region: KP “Zhytomyrteplokumenergo” ZhMR, LLC “Cersanit Invest,” LLC “OBIO,” PJSC “Korosten MDF Plant,” LLC “Monsarto Seeds.” Such accounting allows for the control of pollution sources and the implementation of measures to minimize the negative impact on the environment and public health.

It is possible to assess the state of atmospheric air in the city of Zhytomyr using online monitoring services (Fig. 2), which provide general information about air quality in real time.

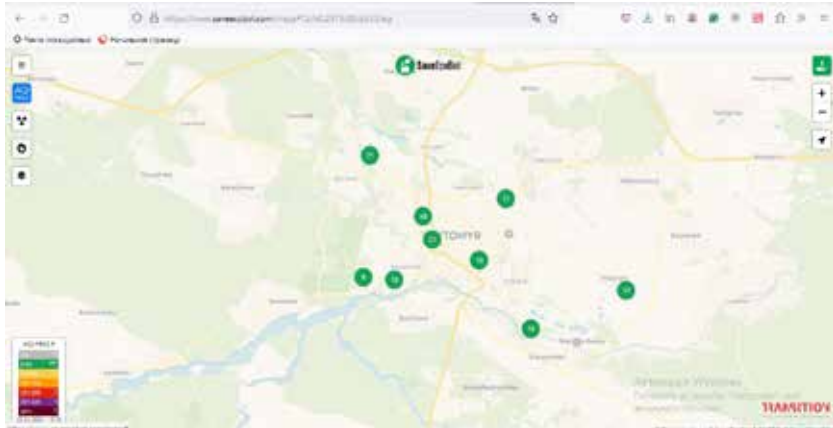


Fig. 2. Overall assessment of atmospheric air quality in real time online⁷⁵

Individual indicators, such as concentrations of major pollutants, air temperature, humidity, atmospheric pressure, and wind speed, are available on specialized meteorological portals (Fig. 3). However, it should be noted that such information is for reference only: it does not always reflect the dynamics of pollution changes and does not contain data on potential hazards to humans and the environment.

The Earth's atmosphere is a gaseous envelope of the planet that was formed as a result of complex exogenous and endogenous processes. The main gases are nitrogen and oxygen, with nitrogen being considered inert and its concentration relatively stable, although it may increase slightly due to natural phenomena, such as volcanic emissions. In addition, the atmosphere contains argon, carbon dioxide, water vapor, and other impurities that affect meteorological processes and the chemical balance of the air.

Constant monitoring of air pollutant levels and compliance with established standards are necessary to preserve ecological balance and public health. This requires not only state registration of enterprises that produce emissions, but also the development and implementation of modern methods for monitoring, assessing, and forecasting the ecological state of the atmosphere.

⁷⁵ Якість повітря у місті Житомир. URL: <https://www.saveecobot.com/maps/zhytomyr> (дата звернення: 15.01.2025).

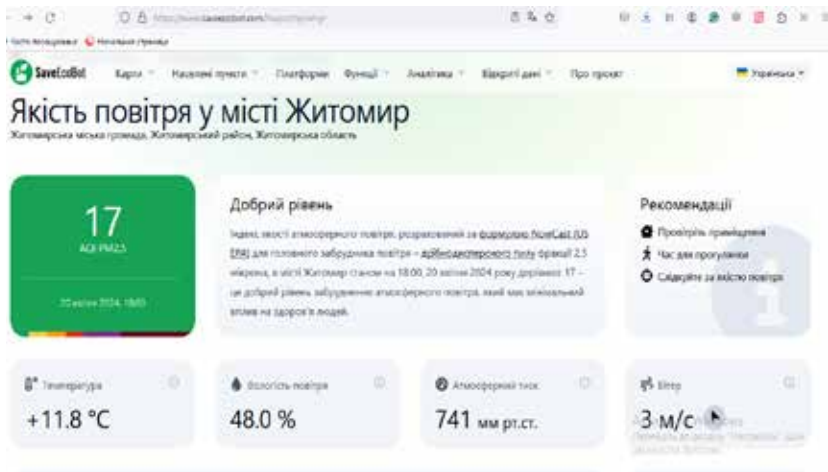


Fig. 3. General indicators of atmospheric air quality in real time online

Given the current challenges, in particular the intensification of industrial activity and the impact of climate change, a systematic approach to atmospheric air management is important, including: modernization of emission sources, optimization of pollution standards, development of air purification technologies, and international cooperation in the field of ecology. This approach provides a comprehensive assessment of the state of the atmospheric basin and effective measures to prevent negative impacts on the environment and human health.

2. Sources of atmospheric pollution and their environmental consequences

In modern conditions of increasing anthropogenic pressure on the environment, it is becoming increasingly important to study the factors that pose environmental risks to natural systems and public health. Particular attention should be paid to analyzing sources of pollution, the nature of their impact, and the consequences of harmful substances entering natural components, which allows for the justification of environmental control and management decisions. Thus, in addition to constant gas components, atmospheric air contains a variable part represented by various impurities, the concentration and composition of which depend on the intensity of natural and anthropogenic processes. These impurities enter the atmosphere as a result of stationary and mobile sources of pollution, which shape local and regional air quality characteristics.

Among the substances that enter the atmospheric air, compounds with proven carcinogenic effects on humans pose a significant danger. According to the order of the Ministry of Health of Ukraine dated 20.06.2022 No. 1054, humans людини (nakaz MOZ Ukrainy vid 20.06.2022 № 1054), some of these pollutants belong to the first group of carcinogens. This group includes asbestos, arsenic and its compounds, aflatoxins, benz(a)pyrene, beryllium and its compounds, chloromethyl methyl ether, diesel engine gases, mustard gas, coal tar and pitch, N-nitrosornicotine, silicon oxide, nickel and its compounds, toluidine, hexavalent chromium compounds, and 2,3,4,7,8-pentachlorodibenzo-furan. A significant proportion of these substances enter the human body through inhalation, which increases the risk of developing chronic and oncological diseases.

Air pollution causes ecological imbalance and intensifies negative anthropogenic processes, which manifests itself, in particular, in the transformation of the vegetation cover of natural and urbanized areas. Plant communities are among the first components of ecosystems to respond to changes in the quality of atmospheric air, as they are in direct contact with pollutants throughout the growing season.

The action of pollutants causes physiological disorders in plants, in particular changes in the intensity of photosynthesis, gas exchange processes, transpiration, and mineral nutrition, which leads to a decrease in the productivity and viability of plant organisms. Under conditions of prolonged and systematic exposure to pollutants, they accumulate in plant tissues, causing anatomical and morphological changes in vegetative organs, in particular leaves and shoots. Such changes can manifest themselves in the disruption of the leaf blade structure, changes in cuticle thickness, degradation of conductive tissues, asymmetry of organs, and inhibition of growth processes. The combination of these reactions reflects the level of anthropogenic pressure on ecosystems and confirms the feasibility of using plants as sensitive indicators of atmospheric air quality in environmental monitoring systems.

In this regard, plants are widely used as sensitive bioindicators in biotic monitoring systems, in particular phytomonitoring, which allows assessing the level and spatial differentiation of atmospheric air pollution. Bioindication indicators reflect the cumulative impact of a complex of pollutants and are informative for long-term environmental observations. It has been established that air pollutants cause disturbances in the indicators of fluctuating asymmetry of the leaf blade of *Betula pendula* Roth, which is considered a sensitive indicator of environmental stress and destabilization of

plant growth conditions^{76, 77}. An increase in the level of asymmetry indicates a decrease in the adaptive capacity of plant organisms and can be used for a comprehensive assessment of the ecological status of territories.

The negative impact of atmospheric pollutants has also been confirmed by numerous experimental studies on animals. Air pollution accelerates the development of pathological processes, reduces the adaptive capacity of the organism, and decreases the chances of survival. Pollutants cause morphological changes in the vessels of vital organs at the tissue level and can also be factors in the onset and progression of autoimmune diseases, particularly rheumatic diseases. The results obtained are reasonably extrapolated to humans^{78, 79}.

The atmospheric basin of the Zhytomyr region is formed by a combination of basic gas components and additional impurities, which can be either permanent or temporary. In terms of their functional significance, these components are divided into those necessary for human life and those that are inert. Products of anthropogenic activity are impurities that have a negative impact on the human body and the environment. Some of them contribute to the destruction of the ozone layer, while others exacerbate the greenhouse effect and global climate change processes. Pollution of the atmospheric basin of the Zhytomyr region is caused by both natural and anthropogenic sources. Natural factors include wind erosion of soil, which causes soil particles, biological material, and residues of agrochemicals, including fertilizers and pesticides, to be lifted into the air and carried over long distances.

The leading anthropogenic source of atmospheric pollution in the region is motor transport. The composition of toxic components released into the atmosphere in 2021 is shown in the diagram (Fig. 4).

⁷⁶ Біоіндикаційна оцінка впливу техногенного навантаження від забруднення атмосферного повітря в умовах змін промислової інфраструктури регіону / В. В. Бойко, Л. Д. Пляцук, Л. Г. Філагов, І. О. Трунова. *Вісник КрНУ імені Михайла Остроградського*. 2012. № 73. С. 150–153.

⁷⁷ Khannanova O. R., Arkanova A. A. Bioindication assessment of the atmospheric air of poltava municipal park. *Biolohiia ta ekolohiia*. 2017. Vol. 3 (1–2). P. 69–75.

⁷⁸ Identification of an Association of TNFAIP3 Polymorphisms With Matrix Metalloproteinase Expression in Fibroblasts in an Integrative Study of Systemic Sclerosis-Associated Genetic and Environmental Factors / P. Wei, Y. Yang, X. Guo et al. *Arthritis & rheumatology (Hoboken, N. J.)*. 2016. Vol. 68, № 3. P. 749–760. <https://doi.org/10.1002/art.39476>

⁷⁹ Вплив ксенобіотиків у повітрі на перебіг ангіопатії у щурів з моделлю системного аутоімунного ревматичного захворювання / Є. Д. Єгудіна, Г. С. Такташов, В. Я. Мікукста та ін. *Здобутки клінічної і експериментальної медицини*. 2017. № 1. С. 32–37. <https://doi.org/10.11603/1811-2471.2017.v0.i1.7335>

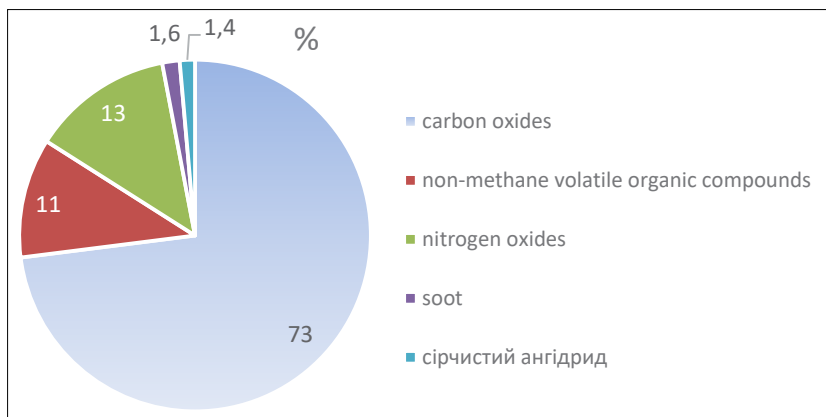


Fig. 4. Component composition of toxic substances released into the atmospheric air of the Zhytomyr region in 2021

These compounds have a negative impact on the ozone layer, the respiratory systems of humans and animals, and vegetation. In addition, they contribute to acid rain, climate change, and the deterioration of the overall ecological situation, which makes it difficult for ecosystems to adapt to increasing anthropogenic pressure. Elevated concentrations of carbon monoxide disrupt oxygen transport processes in the body, which is especially dangerous for people with chronic diseases of the cardiovascular and respiratory systems. Solid particles, in particular soot fractions, accumulate in the lungs and can cause inflammatory processes and the development of severe respiratory pathologies⁸⁰ [80].

Assessing changes in pollution indicators over time is an important tool for analyzing the effectiveness of environmental protection measures and identifying general patterns of the impact of socio-economic and external factors on the state of the environment. Analysis of statistical data makes it possible to track fluctuations in emissions and identify periods of increase or decrease. Analysis of the dynamics of pollutant emissions into the atmosphere shows that there is no consistent trend towards their constant reduction or increase. During the period under review, there were alternating phases of decline and increase in emissions, which was due to changes in the level of industrial activity, the intensity of transport flows, and the influence of economic and social factors. The total emissions from all sources of pollution are shown in Fig. 5.

⁸⁰ Patseva I., Kahukina A. Analysis of the atmospheric air state in the city of Zhytomyr. Sloboda. *Scientific Journal. Natural Sciences*. 2024. Vol. 1. 77–81. doi.org/10.32782/naturalspu/2024.1.10

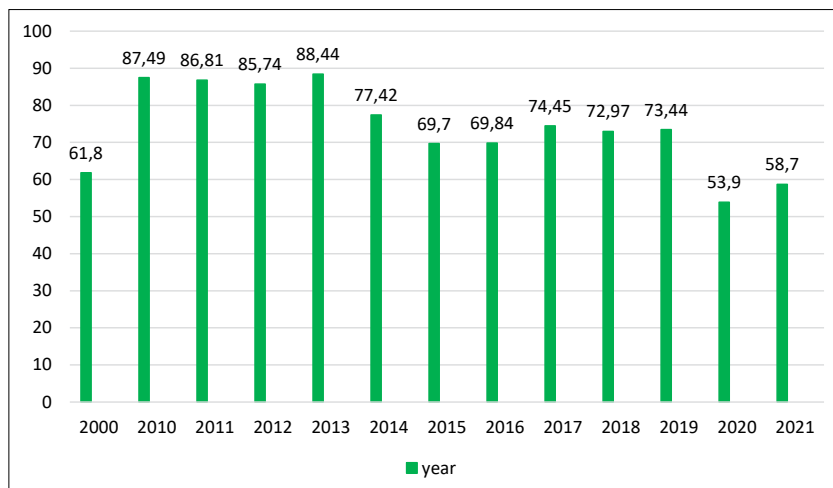


Fig. 5. Volumes of pollutant emissions into the atmosphere in Zhytomyr region in 2000–2020 (thousand tons)

At the same time, a comprehensive analysis of the current situation is complicated by the limited availability of official statistical information. Data on pollutant emissions in 2022–2023 were not published by the Main Statistical Office due to the introduction of martial law. This situation limits the possibility of a comprehensive assessment of the impact of military actions on the dynamics of anthropogenic load and requires the use of alternative sources of information and predictive approaches. The results obtained indicate the need to further improve the environmental monitoring system, in particular to ensure the continuity of data collection and publication even in emergency situations. This will increase the reliability of assessments of the environmental status of territories and enable the formulation of scientifically sound recommendations for reducing pollution levels.

An analysis of pollutant emission trends over the past 12 years shows significant variability in indicators over time. The lowest emissions were recorded in 2020, while the highest volumes were in 2013, reflecting periods of varying intensity of economic and transport activity (Fig. 5). In 2020–2021, there is a clear trend towards a decrease in total emissions: the reduction was 19.54 t and 14.74 t, respectively, which in relative terms corresponds to a decrease of 73.4% and 79.9%. The observed decrease in emissions during this period may be associated with a decline in industrial activity, restrictions on transport flows, and general socio-economic changes. At the same time,

it should be noted that the total indicator was formed by emissions from both stationary and mobile sources of pollution, whose contribution varies depending on the year of observation (Fig. 5).

An analysis of long-term trends in pollution sources shows that mobile sources continue to dominate in terms of total pollutant emissions. Over the past twenty years, their contribution has systematically exceeded emissions from stationary sources, as clearly shown in Figure 6 (with the exception of 2022–2023, for which no official statistics are available). On average, emissions from mobile sources were 3.5–4 times higher than those from stationary sources, indicating the decisive role of the transport sector in polluting the region’s atmospheric basin. Stationary sources are characterized by significant variability in emissions over time. The minimum values were recorded in 2015, while the maximum values were recorded in 2011, with a difference of about 2.3 times between the extreme values. Such fluctuations may be related to changes in the structure of industrial production, the level of capacity utilization of enterprises, and the introduction or absence of environmental protection measures.

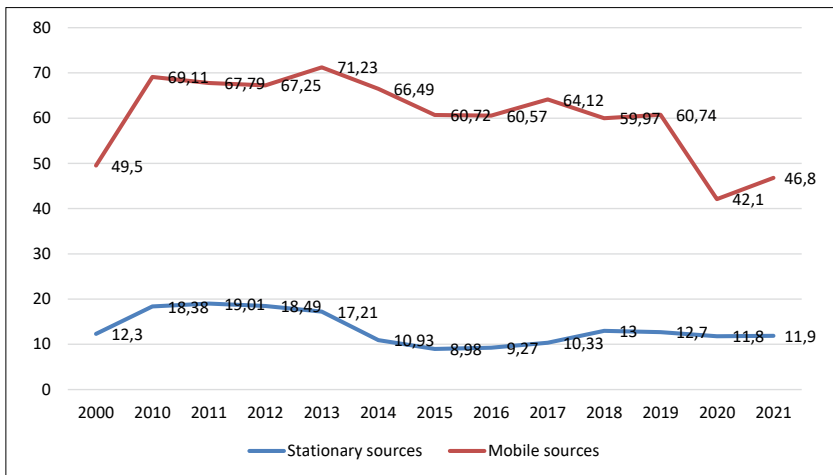


Fig. 6. Comparative dynamics of pollutant emissions into the atmospheric basin of Zhytomyr region (thousand tons)

The dynamics of emissions from mobile sources are more smoothed out, but also show clearly defined extreme values. The lowest emissions were recorded in 2020, which is probably due to a decrease in traffic intensity, while the highest values were recorded in 2013. The difference between the minimum and maximum values for this group of sources was about 1.7 times.

The results confirm that mobile sources are the main anthropogenic load on the atmospheric basin of the Zhytomyr region. This justifies the need to focus environmental protection measures on reducing transport emissions, in particular by optimizing transport infrastructure, renewing the vehicle fleet, and introducing environmentally friendly fuels.

For a comprehensive assessment of the spatial characteristics of anthropogenic load, it is advisable to use relative indicators that allow comparing emission volumes with the area of the territory. Such indicators make it possible to assess the intensity of pollution more objectively and identify periods with increased or decreased environmental load.

One of the important integral indicators characterizing the spatial distribution of pollutant emissions and their concentration levels over the region is the emission density, calculated per unit area (1 km²) and expressed in kilograms. This indicator makes it possible to assess the intensity of anthropogenic pressure on the atmosphere regardless of administrative boundaries and territory size, which is especially important for regions with a heterogeneous economic structure (Fig. 7).

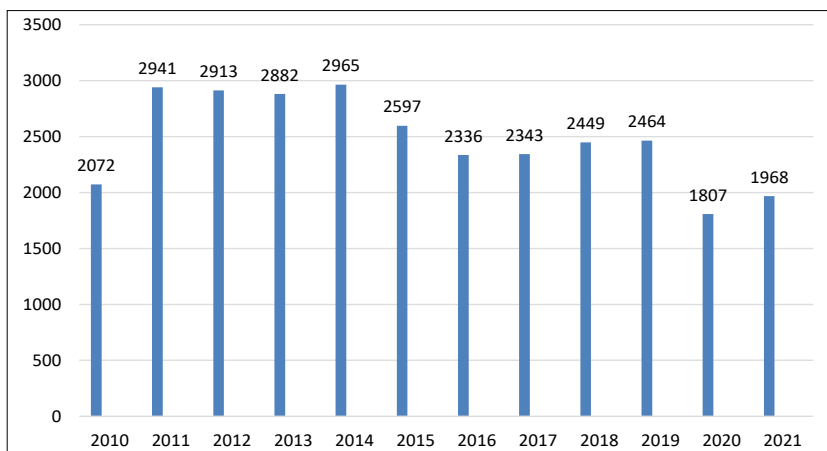


Fig. 7. Density of emissions distribution in the atmospheric basin of Zhytomyr region (kg per 1 km²)

Emissions density allows for a correct comparison of pollution levels at different times, as well as tracking trends in its growth or decline over time. In addition, this indicator is informative when analyzing the effectiveness of environmental protection measures and changes in the structure of pollution sources, in particular the ratio of stationary and mobile sources.

Data on the density of pollutant emissions within the Zhytomyr region are presented in Diagram 7, which clearly shows the spatial and temporal dynamics of anthropogenic impact on the region's air basin.

Analysis of the data presented shows that the lowest emission density values were recorded in 2020, while the highest values were recorded in 2014. The difference between the minimum and maximum density levels was about 1.4 times, indicating relatively moderate but stable fluctuations in the intensity of anthropogenic load in space.

The decrease in emission density in certain years may be associated with a decline in industrial activity, a reduction in transport flows, and the implementation of environmental protection measures. At the same time, periods of elevated values reflect an increase in anthropogenic pressure on the atmospheric basin, which requires tighter control over sources of pollution and improvement of the environmental monitoring system.

To assess the real anthropogenic load on the population, it is advisable to use relative indicators that take into account not only the total volume of emissions but also the number of inhabitants in the territory. Such indicators allow for a better reflection of the potential impact of pollution on humans and enable accurate interannual comparisons.

One of the informative indicators characterizing the environmental load is the volume of pollutant emissions per capita per year. This indicator is illustrative because it allows assessing the conditional "share" of pollution attributable to each inhabitant of the region. Given that 1 liter of air weighs approximately 0.001225 kg, even relatively small concentrations of pollutants become significant when converted to annual human air consumption.

In some years, emissions per person in the Zhytomyr region reached about 70 kg per year, which is equivalent to approximately 192 g per day. These values indicate a significant level of anthropogenic load and potential risks to public health. The dynamics of changes in this indicator over the last twenty years are shown in Figure 8. Analysis of time series shows that the minimum emissions per capita were recorded in 2000, while the maximum were recorded in 2013. The difference between the minimum and maximum levels was about 1.6 times. The identified pattern is consistent with the dynamics of total emissions, in particular with their peak values in 2013 (Fig. 8), which confirms the close relationship between absolute and relative pollution indicators.

The results obtained emphasize the expediency of using the per capita emissions indicator as an important tool for environmental assessment, which allows for a more objective analysis of changes in anthropogenic pressure and the formulation of scientifically sound recommendations for reducing pollution levels.

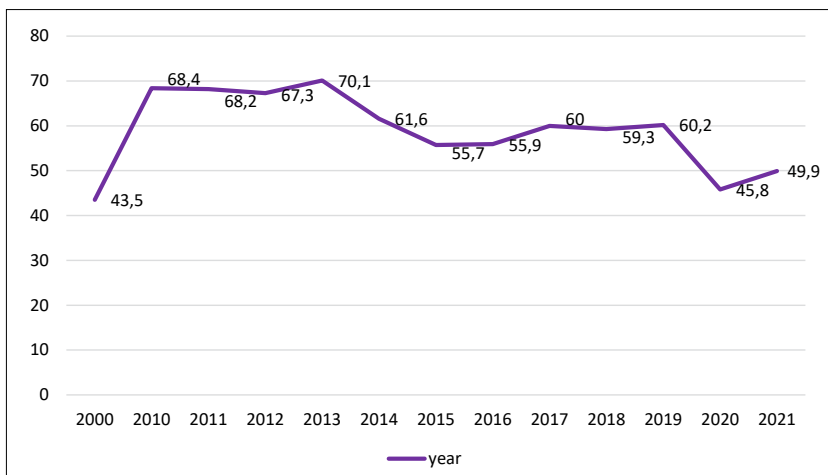


Fig. 8. Emissions in the atmospheric basin of Zhytomyr region (kg per person)

CONCLUSIONS

Assessment of the state of the atmospheric environment is one of the key indicators of a region's environmental well-being and an essential component of the environmental safety system. It enables not only the recording of current pollution levels but also the identification of priority areas for environmental protection activities aimed at reducing anthropogenic pressure on the environment. The application of a set of absolute and relative pollution indicators provides a more comprehensive and objective assessment of the impact of various groups of emission sources on ambient air quality, ecosystems, and public health.

The results of long-term studies confirm that atmospheric pollution is not only local in nature but also transregional and global, which necessitates coordinated actions at both national and international levels. In this context, compliance with environmental standards and the implementation of environmentally oriented approaches in the industrial, transport, and energy sectors become particularly relevant. An analysis of emission dynamics within Zhytomyr Oblast over the past twenty years has demonstrated a persistent trend of mobile pollution sources dominating over stationary ones, leading to the formation of elevated concentrations of carbon monoxide, particulate matter, and potentially carcinogenic compounds in the near-surface layer of the atmosphere.

It was established that the most strained environmental situation in terms of atmospheric pollution was observed in 2013, while the minimum values were recorded in 2020, reflecting the influence of socio-economic and technogenic factors on emission formation. An analysis of specific pollution indicators calculated per capita confirms the identified patterns and indicates a close relationship between total emission volumes and the level of individual environmental burden on the region's population. This situation has direct consequences for human health, the functioning of biota, and the stability of natural ecosystems.

The generalized results of the study indicate the need to apply an integrated and systemic approach to reducing anthropogenic impacts on the atmospheric environment. This includes modernization of transport infrastructure, development of environmentally friendly modes of transport, implementation of advanced emission reduction and air purification technologies, realization of regional environmental programs, as well as strengthening state and public control over compliance with ambient air quality standards.

Systematic monitoring of the air basin and analysis of its spatio-temporal dynamics at the regional level provide a scientific basis for the development of well-grounded management decisions aimed at improving the environmental situation, enhancing the quality of life of the population, and ensuring the sustainable development of territories.

SUMMARY

The current state of the environment has a direct impact on human health and the functioning of ecosystems, and atmospheric air is one of the key components of the environment. Increased anthropogenic pressure, in particular emissions of harmful substances from stationary and mobile sources, causes degradation of the air basin, negatively affects biota, and contributes to the development of diseases in the population. Monitoring the volume and composition of emissions in regions with developed transport and industrial infrastructure is a particularly pressing issue.

The aim of the study was to investigate the ecological state of the atmospheric basin of the Zhytomyr region, analyze the dynamics of air pollution, and assess the impact of stationary and mobile sources on air quality. Analytical review, descriptive and comparative analysis, statistical and cartographic methods, as well as assessment of emissions per capita were used.

The results of the study showed that over the past two decades, emissions from mobile sources have consistently exceeded emissions from stationary sources by 3.5–4 times. The highest pollution levels were recorded in

2013, and the lowest in 2020. The main source of pollution remains motor transport, with carbon oxides and particulate matter dominating its emissions. The amount of pollution per capita demonstrates the level of pressure on the atmosphere from various sources of pollution. The study confirmed the significant impact of anthropogenic factors on the state of the atmosphere and emphasized the need for continuous monitoring and implementation of measures to reduce air pollution.

The data obtained can be used to improve state environmental control, develop regional air protection programs, and plan measures to minimize the negative impact on the population and the environment.

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