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Air pollution and cataract – literature review with local evidence

Zanieczyszczenie powietrza i zaćma – przegląd literatury wraz z lokalnymi danymi

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Abstract

Introduction and Objective. Cataract is a leading cause of vision loss worldwide, with prevalence rising with populations age. It often progresses slowly, causing the patient to underestimate the severity of this issue. Its pathogenesis involves oxidative stress in the eye lens, resulting in lipid peroxidation, crystalline protein oxidation and impaired antioxidant defences. Although this is a natural part of the ageing process, environmental factors, particularly air pollution, may exacerbate the situation. The aim of the review is to present the latest global evidence linking air pollution with cataract formation, and to present the available epidemiological data in Poland, given Poland's high levels of ambient air pollution. Understanding this local landscape is essential for developing targeted ophthalmic prevention programmes.
Brief description of the state of knowledge. Evidence indicates that exposure to air pollution and heavy metals may increase the risk of cataract through enhanced reactive oxygen species (ROS) production and metal accumulation in the lens. However, results are heterogeneous, reflecting variations in divergent diagnostic criteria, exposure assessment methods, and confounding factors. In Poland, there is a notable lack of longitudinal studies currently integrating exposure data with air quality and cataractogenesis, highlighting a gap in the national evidence base.
Summary. Air pollution appears to contribute to cataract pathogenesis via oxidative mechanisms. Improving environmental air quality may reduce the risk of lens opacity. Nevertheless, further well-designed research, particularly in the Polish population, is necessary to quantify the impact of pollution on cataract development and inform preventive strategies.

Key words

particulate matter, air quality, nitrogen dioxide, eye diseases, sulphur dioxide, oxidative stress

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Streszczenie

Wprowadzenie i cel pracy. Zaćma jest jedną z głównych przyczyn utraty wzroku na całym świecie, a jej częstość występowania rośnie wraz ze starzeniem się społeczeństwa. Choroba ta często rozwija się powoli, co sprawia, że pacjenci nie doceniają wagi tego problemu. W jej patogenezie występuje stres oksydacyjny w soczewce oka, prowadzący do peroksydacji lipidów, utleniania białek soczewki oraz osłabienia antyoksydacyjnych mechanizmów obronnych. Sytuację tę mogą pogarszać czynniki środowiskowe, a zwłaszcza zanieczyszczenie powietrza. Naszym celem jest przegląd najnowszych globalnych dowodów na to, że z powstawaniem zaćmy związane jest zanieczyszczenie powietrza oraz przedstawienie dostępnych danych epidemiologicznych dotyczących Polski, z uwzględnieniem poziomu zanieczyszczenia powietrza. Zrozumienie lokalnej sytuacji jest potrzebne do opracowania programów profilaktyki okulistycznej.
Opis stanu wiedzy. Istnieją dowody na to, że narażenie na zanieczyszczenie powietrza i metale ciężkie może zwiększać ryzyko wystąpienia zaćmy poprzez zwiększone wytwarzanie reaktywnych form tlenu (ROS) oraz gromadzenie metali w soczewce. Wyniki badań są jednak niejednolite, co wynika z różnic w stosowanych kryteriach diagnostycznych, metodach oceny narażenia oraz czynnikach zakłócających. W Polsce odnotowuje się wyraźny brak badań długoterminowych łączących dane dotyczące narażenia na zanieczyszczenie powietrza z kataraktogenezą, co uwidacznia lukę w krajowej bazie.
Podsumowanie. Wydaje się, że zanieczyszczenie powietrza przyczynia się do powstawania zaćmy za sprawą mechanizmów oksydacyjnych. Poprawa jakości powietrza w otoczeniu może zmniejszyć ryzyko zmętnienia soczewki. Niemniej jednak konieczne są dalsze, dobrze zaprojektowane badania, zwłaszcza w populacji polskiej, aby oszacować wpływ zanieczyszczenia na rozwój zaćmy i opracować strategie profilaktyczne.

Słowa kluczowe

stres oksydacyjny, dwutlenek węgla, jakość powietrza, pył zawieszony, choroby oczu, dwutlenek siarki

INTRODUCTION AND OBJECTIVE

Cataract and lens opacity are the leading causes of vision loss worldwide, and one of the most common causes of significant visual impairment. Their prevalence is increasing due to the ageing population [1, 2]. In Poland, according to POLSENIOR2 research, 22.6% of people aged 60 and above report having been diagnosed with cataract. The disease is more common in women and people with lower levels of education [3–5].

The lens of the eye is a transparent, avascular structure, composed mainly of epithelial cells and fibres, covered by a capsule. The central part consist of lens nucleus, surrounded by the cortex. Lens epithelial cells proliferate throughout life, migrating to the equatorial zone as they differentiate into new fibres, leading to a progressive increase in its volume and mass. Under physiological conditions, mature lens fibres do not undergo apoptosis. Their longevity and lack of organelles ensure transparency and minimise light scattering [6]. Apoptosis of entire lens epithelial cells is a pathological phenomenon, observed mainly in the development of diseases or under the influence of stress factors. This leads to pathologies in this structure [7].

Oxidative stress in the eye lens is the main mechanism leading to lens opacity [8–10]. Excess reactive oxygen species (ROS) in the lens, arising from such factors as ultraviolet exposure, diabetes, ageing or air pollution – can trigger lipid peroxidation of cell membranes and oxidise crystalline proteins. These changes promote protein aggregation, reduce lens transparency, and ultimately, disturb normal lens homeostasis [11–15]. ROS causes proteins to fold abnormally, triggering an unfolded protein response (UPR) as the body attempts to protect its own tissues. Chronic stress leads to the deregulation of repair processes for incorrectly folded proteins, resulting in the accumulation of defective proteins, the activation of proapoptotic pathways and the death of lens cells, alongside the progression of cataractogenesis [12, 16]. At the same time, the natural antioxidant defences of the lens, including glutathione (GSH), superoxide dismutase (SOD) and catalase, become less effective. Oxidation modifications creates protein-glutathione mixed disulphides (PSSG), which in healthy lens GSH and redox enzymes (e.g. thioltransferase – TTase) maintain transparency. When homeostasis is disrupted, those compounds aggregate and accumulate in proteins, resolving high-molecular-weight aggregates (HMW) destroying lens structure [11]. Another aspect involves the loss of gap junctions responsible for intercellular communication. Lens is an avascular structure, which means those elements are essential for maintaining the internal circulatory system and its metabolism. At the root of this process lies the stress-induced dysfunction of connexins (building blocks of gap junctions), which impairs the transport of antioxidants and nutrients, further accelerating protein aggregation [12].

Exposure to fine particulate matter in aerosols, specifically particles smaller than 2.5 μm ($PM_{2.5}$) and 10 μm (PM_{10}), as well as nitrogen oxides (NO_2) and sulphur oxides (SO_2), increases ROS production on the ocular surface and within the lens [17–20]. In addition, heavy metals found in polluted environments (cadmium, lead, mercury etc.) can accumulate in the lens, where they act as catalysts and further amplify oxidative stress [14, 21]. Some studies suggest that chronic exposure to PM, and NO_2 may additionally induce ferroptosis, a specific form of cell death reliant on iron and oxidative stress in lens cells, further accelerating the development of opacity. Dysfunction in iron metabolism is confirmed by changes in the expression of proteins responsible for its transport and storage (TFRC, FTL, FTH1), leading to the accumulation of free iron and increased oxidative stress [12]. Markers of ferroptosis (e.g. reduced GPX4 activity, increased Fe^{2+} levels and enhanced lipid peroxidation) are present in both animal models and in humans exposed to $PM_{2.5}$ [17]. In this way, air pollution, combining the effects of oxidative stress with metal build up and antioxidant dysfunction, is a significant risk factor for cataract formation [15–27]. Exposure to household pollutants, such as long-term use of solid fuels for cooking (i.e. wood, coal, etc.) has also been associated with a higher risk of the disease [28].

In recent years, a growing number of global epidemiological cohort and cross-sectional studies have reported that there may be air pollutants – in particular $PM_{2.5}$, PM_{10}, NO_2 and SO_2 – which can increase the risk of developing cataract and the need for lens removal surgery [10, 18, 20, 23, 25, 29–34]. Although direct epidemiological studies linking these factors in the Polish population are currently limited, the high levels of particulate matter combined with the significant number of cataract surgeries performed annually, highlight the importance of considering air quality as a potential environmental risk factor in this area.

The aim of this study is to review the current literature on the relationship between air pollution and cataract development. The study also incorporates local evidence to illustrate the environmental context and underline the need for further research in highly polluted regions.

DESCRIPTION OF THE STATE OF KNOWLEDGE

A literature search was used to obtain the most recent articles from PubMed/MEDLINE, Scopus, Web of Science and Google Scholar databases up to October 2025, using the following key words: 'cataract', 'air pollution', 'heavy metals', 'metal accumulation', '$PM_{2.5}$', 'PM_{10}', 'NO_2', 'SO_2' and 'Poland'. The inclusion criteria were epidemiological studies (cohorts, reviews), meta-analyses and original works. Publications were limited to those in Polish or English. Statistical data from the National Health Fund (NFZ) regarding the number of cataract operations was also used. The studies reviewed showed statistically significant associations between long-term exposure to particulate matter and the risk of developing cataract.

Li et al. in a cohort study of more than 400,000 individuals from the Chinese population demonstrated that long-term exposure to $PM_{2.5}$ significantly increases the risk of age-related cataracts in middle-aged and older adults. Their findings showed that each 10 μg/m^3 rise in ambient $PM_{2.5}$ concentration was associated with a 14% increase in cataract risk (HR = 1.14; 95% CI: 1.08–1.21), with a relationship further supported by dose-response analyses. The authors estimated that up to 24.6% of cataract cases in the study population could be attributed to $PM_{2.5}$ exposure, underscoring the substantial influence of this environmental factor on cataract development [10].

Similar results have also been reported in Korea. Shin et al. found that people aged over 50 who were exposed to higher levels of air pollution – particularly PM_{10}, nitrogen dioxide (NO_2) and sulphur dioxide (SO_2) – had a noticeably higher risk of developing cataract. This supports the idea that air pollution plays a real role in cataract formation worldwide. Additionally, the results of the study indicate that people living in areas with higher risk of developing cataract require surgical treatment. This relationship is particularly visible for women over the age of 65. Furthermore, exposure to ozone (O_3) shows an inverse relationship, suggesting a potential protective effect, although the mechanism of this phenomenon requires further study [23].

In European populations, similar findings have come from France. Gayraud et al., in a prospective study, reported that older adults who were exposed to higher levels of air pollution – especially nitrogen dioxide (NO_2) above 40 μg/m^3 – had a noticeably higher chance of needing cataract surgery. People living in areas with the highest NO_2 levels showed about a 46% increase in the risk of undergoing cataract surgery compared to those in cleaner areas (HR = 1.46; 95% CI: 1.16–1.84; p = 0.001). Interestingly, the study did not find any clear link between $PM_{2.5}$ and soot from incomplete fuel combustion with cataract risk in this particular group. These results confirm that NO_2 is a major modifiable risk factor for the development of cataracts [18].

In the British population, prospective analyses by the UK Biobank have shown that prolonged exposure to suspended air pollutants ($PM_{2.5}$, PM_{10}) and nitrogen oxides (NO_2, NO_x) is also associated with a markedly elevated risk of developing cataracts and a necessity for cataract surgery. A study by Chua et al., involved more than 430,000 participants, in which higher concentrations of $PM_{2.5}$, NO_2 and NO_x were associated with a 5–14% increased risk of cataract surgery, showing a dose-response relationship [25]. Yuan et al. confirmed that $PM_{2.5}$ is most strongly associated with the transition from health to coexisting dementia and higher mortality [31]. Li et al. found that people in the highest quartile of combined exposure to several pollutants, e.g. $PM_{2.5}$, PM_{10} and NO_2, had about a 13% higher risk of developing cataracts.

There is a possibility that different pollutants might have additive or even synergistic effects [32]. In another study, Wang Z et al. used data from the UK Biobank to investigate how exposure to $PM_{2.5}$, PM_{10}, NO_2 and NO_x relates to the risk of the five most common vision-threatening eye diseases – cataract being one of them. This analysis showed that exposure to high concentrations of PM_{10} and NO_x was significantly associated with an increased risk of developing ophthalmic diseases [33].

Systematic reviews and meta-analyses by Grant (2022) and Millen confirm that exposure to air pollution, especially particulate matter ($PM_{2.5}$, PM_{10}), nitrogen oxides (NO_2, NO_x) and sulphur dioxide (SO_2), is significantly associated with an increased risk of developing cataracts in adults [20, 34]. Grant's results indicate moderate, but significant, associations between PM_{10} and cataract, while the results for $PM_{2.5}$ are less clear. Millen emphasises that the risk of cataract increases with exposure to $PM_{2.5}$, PM_{10}, NO_2, NO_x and SO_2, while the association with ozone (O_3) is less consistent.

Other studies have also shown that socio-economic factors can modify the impact of exposure to air pollution. People living in areas with lower incomes and higher traffic volumes are more likely to develop lens opacity [27]. Chronic exposure to household pollution associated with the use of solid fuels for cooking also increases the risk of cataract, especially in women [28].

A recent population study from the United States looked at how the levels of nine different metals in urine related to the risk of developing cataract. The researchers used data from the National Health and Nutrition Examination Survey and applied several advanced statistical approaches to sort out the patterns. They found that people with higher urinary levels of Barium (Ba), antimony (Sb) and thallium (Tl) separately, were more likely to have cataract, even after adjusting for a range of other factors. When they analysed mixtures of metals rather than looking at each one individually, cadmium (Cd), lead (Pb) and barium (Ba) showed the strongest negative health associations, whereas cobalt (Co) and tungsten (W) showed the strongest positive correlations with cataract risk. The link between cobalt and cataract stood out the most. This was backed up by Network analysis which indicated the involvement of interleukin-4 and interleukin-13 signalling pathways, suggesting that the AKT1 protein may play a part in the underlying disease mechanisms. The results suggest that exposure to any combination of metal mixtures may modulate the risk of cataract by influencing inflammatory pathways and regulating cellular homeostasis [35].

A study by Jiang et al. showed a global increase in the number of cataract cases and the total burden of the disease measured as disability-adjusted life years (DALYs), mainly due to ageing populations and population growth. At the same time, a decrease in standardised DALY rates has been observed, reflecting improvements in treatment and access to surgical interventions. The authors highlighted significant regional and gender inequalities – the highest burden is in regions with low socio-demographic index (SDI), and among women, while air pollution remains one of the key modifiable risk factors for cataract development, especially in countries with low SDI [36]. Wang D et al. showed that the global burden of cataract attributable to particulate matter pollution, smoking, hyperglycaemia and high BMI is declining in standardised terms, but continues to increase in regions with low and medium SDI. Reducing exposure to PM, quitting smoking, controlling glycaemia and body weight, are key to preventing cataract, especially for older people [37]. Grant A et al. (2021), in a large population-based study from Canada, reported that higher $PM_{2.5}$ levels were clearly linked with a greater risk of visual impairment, glaucoma and AMD. The association with cataract was weaker and did not reach statistical significance. Overall, their findings suggest that $PM_{2.5}$ could play a role in age-related eye diseases, but they also point out that more prospective studies are needed to confirm this [38].

According to an epidemiological study by the National Health Fund (NFZ) in Poland, it is estimated that the overall morbidity of cataract stands at over 2,174,600 people, with and annual incidence of 237,000 cases [39]. Cataract is treated through surgical lens replacement; therefore, an analysis of surgical statistics within the Polish healthcare system is provided here. Based on other NFZ statistics regarding cataract surgery procedures performed, it can be seen that in 2024, a total of over 350,000 cataract operations were carried out in Poland. For the purposes of this study, the procedures 'Cataract removal – category I' and 'Cataract removal – category II' have been combined which, together, constitute the total number of cataract procedures reported by hospitals in Poland. It should be noted that operations are reported per eye, meaning that a single patient may potentially undergo surgery on both eyes (in Poland, these are usually performed during separate hospital stays) and performed as a day-case procedure [40]. Some patients in the early stages of cataract development are not eligible for surgery funded by the NFZ, with the percentage of those undergoing surgery reached 65.5% [3]. Unfortunately, the available data only show operations performed in specific centres without a breakdown by the place of residence of the patient. Kaminska et al. report that over 70% of those who surgery lived in urban areas [41].

There is a lack of large-scale studies accounting for the impact of patient migration between centres, migration between the provinces to towns with shorter waiting times for surgery, or difficulties in transporting patients from small towns or villages to larger centres. Further investigation is required in this area [41, 42]. The Polish POLSENIOR2 study confirms a higher incidence of disease among people living in towns and cities with populations of over 50,000, as well as an increase in incidence as the size of the town or city increases. Furthermore, there is a significant growth in incidence in the southern provinces of Poland compared to other regions covered by the study [3]. This distribution is also confirmed by the 2016 epidemiological study of healthcare needs undertaken by the NFZ, which presents morbidity and incidence per 100,000 inhabitants. Data shows a marked increase in the provinces of southern and, to a lesser extent, central Poland, with the highest recorded morbidity rate of 6,941.5 in the Silesian Province in south-west Poland, and the lowest in the Warmian-Masurian Province in the north-east of the country – 4,372.6 The highest recorded incidence was in Silesia at 722.9, and the lowest in Pomerania, a region located in northern Poland – 517,3 [39]. According to data from the NFZ on the number of total cataract operations performed in 2024, the highest number was performed in the Silesian Province – 43,579, followed by the Masovian Province – 31,016, and the Greater Poland Province – 31,016. The fewest were performed in the provinces of Opole – 6,999, Lubusz – 8,641, and Warmia-Masuria – 8,729. Unfortunately these are raw figures for the number of operations, without taking into account the demographics and migrations between provinces, which means that more operations were performed in the larger provinces [40]. Further original studies are needed.

Air pollution is a major health issue in Poland. Levels of particulate matter, nitrogen oxides, sulphur dioxide and benzo(a)pyrene are among the highest in Europe – especially in large cities like Kraków, Łódź, or the numerous agglomerations like Katowice in Upper Silesia. The problem during the heating season of winter, and on cold, still days with little wind, combined pollution tends to build up and linger in the air [43–48]. High concentrations of these pollutants are a consequence of emissions from the municipal and residential sector, transport and industry, as well as the result of ineffective environmental policy and lack of effective tools to enforce air quality standards [45, 46]. Chemical transport models have shown that over 80% of $PM_{2.5}$ emissions originate from individual heating sources [49]. Despite the implementation of air quality improvement programmes such as the Clean Air Programme (*Program Czyste Powietrze*), the effects are limited by the insufficient scale of measures and difficulties in enforcing regulations [45, 50].

The evidence so far suggests that air pollution in Poland is an important, and more importantly, changeable risk factor for cataract development. At the same time, there is still a need for more large-scale studies, specifically in Polish conditions, to obtain a clearer picture of how each pollutant affects cataract risk, and to assess which preventive actions actually make a difference. In the light of current evidence, improving air quality should be considered part of the strategy for preventing diseases of the lens of the eye, especially in the elderly population.

SUMMARY

1) Long-term exposure to air pollution – especially $PM_{2.5}$, PM_{10}, NO_2/NO_x and SO_2 – along with heavy metals in the air, is significantly associated with an increased risk of developing cataracts, as confirmed by cohort studies from Europe, Asia, and analyses by the UK Biobank. This evidence suggests that the impact of air pollution on cataract risk is independent of classic risk factors, such as smoking, age, and metabolic diseases such as diabetes. At the same time, this indicates the need to view air quality as an important determinant of eye health [10, 18, 20, 23, 25, 29–34].
2) The risk to eye health increases in a dose-dependent manner; in some populations, more than 20% of cataract cases can be attributed to exposure to $PM_{2.5}$ [10].
3) Biological mechanisms include oxidative stress, lipid peroxidation, heavy metal accumulation and ferroptosis, which provide a consistent explanation for the observed epidemiological relationships [7–27].
4) Air pollution should be considered a modifiable risk factor for cataract development, and improving air quality may be an important element for prevention, especially in the elderly population [10, 18, 20, 23, 25, 29, 31–34, 36–38].
5) In Poland, where levels of $PM_{2.5}$, PM_{10}, NO_2 and benzo(a)pyrene are among the highest in Europe, prospective cohort studies are needed to accurately assess the impact of environmental exposure on the risk of cataract, and the effectiveness of preventive measures. This could be linked to the National Health Fund (NFZ) disease registries and the number of surgical data, taking into account seasonal and geographical variability of pollution with the population density in individual areas, geographical concentration of cataract cases, as seen in Poland's industrialized and urban regions. Potentially, the use of individual exposure assessment methods and biomarkers of oxidative stress in serum and tears could complement knowledge about pathogenic mechanisms [3, 39–50].

REFERENCES

1. World Health Organization. World report on vision. 2019. Available from: https://www.who.int/publications/i/item/world-report-on-vision; ISBN: 978-92-4-151657-0
2. Pascolini D, Mariotti SP. Global estimates of visual impairment: 2010. Br J Ophthalmol. 2012;96:614–618. doi:10.1136/bjophthalmol-2011-300539
3. Błędowski P, Mossakowska M, Zdrojewski T, et al. Badanie poszczególnych obszarów stanu zdrowia osób starszych, w tym jakości życia związanej ze zdrowiem. Gdańsk: Gdański Uniwersytet Medyczny; 2021.
4. Lange N, Jagiełło K, Bandosz P. Risk factors for self-reports of diagnosed cataracts among older adults in Poland. BMC Public Health. 2025;25:1033. doi:10.1186/s12889-025-21713-8
5. Lange N, Kujawska-Danecka H, Wyszomirski A, et al. Significant improvements in cataract treatment and persistent inequalities in access to cataract surgery among older Poles from 2009 to 2019: results of the PolSenior and PolSenior2 surveys. Front Public Health. 2023;11:271–291. doi:10.3389/fpubh.2023.1201689. PMID: 37900022.

6. Cicinelli MV, Buchan JC, Nicholson M, et al. Cataracts. Lancet Lond Engl. 2023;401:377–389. doi:10.1016/S0140-6736(22)01839-6. PMID: 36565712.
7. Zhang L, Yan Q, Liu J-P, et al. Apoptosis: its functions and control in the ocular lens. Curr Mol Med. 2010;10:864–875. doi:10.2174/156652410793937741. PMID: 21091420.
8. Beebe DC, Holekamp NM, Shui Y-B. Oxidative damage and the prevention of age-related cataracts. Ophthalmic Res. 2010;44:155–165. doi:10.1159/000316481. PMID: 20829639.
9. Cekić S, Zlatanović G, Cvetković T, et al. Oxidative Stress in Cataractogenesis. Biomol Biomed. 2010;10:265–269. doi:10.17305/bjbms.2010.2698
10. Li X, Xie J, Xu J, et al. Long-Term Exposure to Ambient PM2.5 and Age-Related Cataracts among Chinese Middle-Aged and Older Adults: Evidence from Two National Cohort Studies. Environ Sci Technol. 2023;57:11792–11802. doi:10.1021/acs.est.3c02646. PMID: 37534997.
11. Lou MF, Augusteyn RC. Oxidation-Induced Mixed Disulfide and Cataract Formation: A Review. Antioxidants. 2025;14:425. doi:10.3390/antiox14040425
12. Li J, Buonfiglio F, Zeng Y, et al. Oxidative Stress in Cataract Formation: Is There a Treatment Approach on the Horizon? Antioxidants. 2024;13:1249. doi:10.3390/antiox13101249
13. Shu D, Chaudhary S, Cho K-S, et al. Role of Oxidative Stress in Ocular Diseases: A Balancing Act. Metabolites. 2023;13:187. doi:10.3390/metabo13020187
14. Erie JC, Butz JA, Good JA, et al. Heavy Metal Concentrations in Human Eyes. Am J Ophthalmol. 2005;139:888–893. doi:10.1016/j.ajo.2004.12.007
15. Tang Y, Liang H, Su L, et al. Ferroptosis: a new perspective on the pathogenesis of radiation-induced cataracts. Front Public Health. 2024;12:1449216. doi:10.3389/fpubh.2024.1449216
16. Wang Y, Tang M. PM2.5 induces ferroptosis in human endothelial cells through iron overload and redox imbalance. Environ Pollut. 2019;254:112937. doi:10.1016/j.envpol.2019.07.105
17. Sheng F, Gu Y, Hao S, et al. Ferroptosis is involved in the damage of ocular lens under long-term PM2.5 exposure in rat models and humans. Ecotoxicol Environ Saf. 2024;288:117397. doi:10.1016/j.ecoenv.2024.117397
18. Gayraud L, Mortamais M, Schweitzer C, et al. Ambient air pollution exposure and incidence of cataract surgery: The prospective 3City-Alienor study. Acta Ophthalmol (Copenh). 2025;103:e192–e199. doi:10.1111/aos.16790. PMID: 39528362.
19. Zhang X, Liu B, Lal K, et al. Antioxidant System and Endoplasmic Reticulum Stress in Cataracts. Cell Mol Neurobiol. 2023;43:4041–4058. doi:10.1007/s10571-023-01427-4. PMID: 37874455.
20. Grant A, Leung G, Freeman EE. Ambient Air Pollution and Age-Related Eye Disease: A Systematic Review and Meta-Analysis. Invest Ophthalmol Vis Sci. 2022;63:17. doi:10.1167/iovs.63.9.17. PMID: 35960515
21. Jung SJ, Mehta JS, Tong L. Effects of environment pollution on the ocular surface. Ocul Surf. 2018;16:198–205. doi:10.1016/j.jtos.2018.03.001
22. Li M, Gende M, Tovar A, et al. Assessing Chronic Heavy Metal Exposure by Analysis of Human Cataract Specimens and the Relationship to Metabolic Profiles. Curr Eye Res. 2025;50:264–275. doi:10.1080/02713683.2024.2421932
23. Shin J, Lee H, Kim H. Association between Exposure to Ambient Air Pollution and Age-Related Cataract: A Nationwide Population-Based Retrospective Cohort Study. Int J Environ Res Public Health. 2020;17:9231. doi:10.3390/ijerph17249231. PMID: 33321894.
24. Palomino-Vizcaino G, Schuth N, Domínguez-Calva JA, et al. Copper Reductase Activity and Free Radical Chemistry by Cataract-Associated Human Lens γ-Crystallins. J Am Chem Soc. 2023;145:6781–6797. doi:10.1021/jacs.2c13397. PMID: 36918380.
25. Chua SYL, Khawaja AP, Desai P, et al. The Association of Ambient Air Pollution With Cataract Surgery in UK Biobank Participants: Prospective Cohort Study. Invest Ophthalmol Vis Sci. 2021;62:7. doi:10.1167/iovs.62.15.7. PMID: 34874411
26. Morris D, Fraser SG, Gray C. Cataract surgery and quality of life implications. Clin Interv Aging. 2007;2:105–108. doi:10.2147/ciia.2007.2.1.105
27. Wan Y, Wang Y, Zhao L, Wang Z, et al. The Association between Socioeconomic Factors and Visual Function among Patients with Age-Related Cataracts. Meduri A, editor. J Ophthalmol. 2020;2020:1–8. doi:10.1155/2020/7236214
28. Chan KH, Yan M, Bennett DA, et al. Long-term solid fuel use and risks of major eye diseases in China: A population-based cohort study of 486,532 adults. PLoS Med. 2021;18:e1003716. doi:10.1371/journal.pmed.1003716. PMID: 34324491.
29. Han Z, Zhao C, Li Y, et al. Ambient Air Pollution and Vision Disorder: A Systematic Review and Meta-Analysis. Toxics. 2024;12:209. doi:10.3390/toxics12030209. PMID: 38535942.
30. Chan KH, Yan M, Bennett DA, et al. Long-term solid fuel use and risks of major eye diseases in China: A population-based cohort study of 486,532 adults. PLoS Med. 2021;18:e1003716. doi:10.1371/journal.pmed.1003716. Cited in: PMID: 34324491.
31. Yuan K, Song C, Zhong J, Xie M, et al. The Association of Ambient Air Pollution With Dynamic Transitions of Cataract and Dementia: A UK Biobank Study. Int J Geriatr Psychiatry. 2025;40:e70090. doi:10.1002/gps.70090
32. Li Y, Zhang Y, Kam KW, et al. Associations of long-term joint exposure to multiple ambient air pollutants with the incidence of age-related eye diseases. Ecotoxicol Environ Saf. 2025;294:118052. doi:10.1016/j.ecoenv.2025.118052
33. Wang Z, Yu Y, Ye Y, et al. Associations Between Ambient Air Pollution and Five Common Vision-Threatening Ocular Diseases in Middle-Aged and Older Adults: A Large Prospective Cohort Study. Am J Ophthalmol. 2025;274:276–285. doi:10.1016/j.ajo.2025.03.009. PMID: 40057009.
34. Millen AE, Dighe S, Kordas K, et al. Air Pollution and Chronic Eye Disease in Adults: A Scoping Review. Ophthalmic Epidemiol. 2024;31:1–10. doi:10.1080/09286586.2023.2183513. PMID: 36864662.
35. Yang R, Li J, Liu R, et al. Urinary metal mixtures and cataract: Findings from a U.S. population-based study and network pharmacology analysis. Toxicol Lett. 2025;414:111751. doi:10.1016/j.toxlet.2025.111751. PMID: 41135724.
36. Jiang X, Xu B, Zhai J, et al. Global trends in cataract burden: a 30-year epidemiological analysis and prediction of 2050 from the Global Burden of Disease 2021 study. Br J Ophthalmol. 2025 Aug 18; doi:10.1136/bjo-2025-327776
37. Wang D, Tang T, Li P, et al. The global burden of cataracts and its attributable risk factors in 204 countries and territories: a systematic analysis of the global burden of disease study. Front Public Health. 2024;12:1366677. doi:10.3389/fpubh.2024.1366677. Cited in: PMID: 38932770.
38. Grant A, Leung G, Aubin M-J, et al. Fine Particulate Matter and Age-Related Eye Disease: The Canadian Longitudinal Study on Aging. Invest Ophthalmol Vis Sci. 2021;62:7. doi:10.1167/iovs.62.10.7. Cited in: PMID: 34369984.
39. DAiS. Mapa potrzeb zdrowotnych w zakresie chorób oka i okolic dla województwa opolskiego. NFZ; [cited 2026 Mar 17]. Available from: https://basiw.mz.gov.pl/mapa/mapy/woj-opolskie/
40. Statystyka NFZ – Statystyki Świadczenia. NFZ; [cited 2026 Mar 15]. Available from: https://statystyki.nfz.gov.pl/Benefits/1a
41. Kamińska A, Pinkas J, Goryński P, et al. A National Registry-Based Epidemiological Study to Evaluate 395 646 Patients Hospitalized Due to Eye Diseases in Poland in 2019. Med Sci Monit Int Med J Exp Clin Res. 2023;29:e939351-1-e939351-14. doi:10.12659/MSM.939351. PMID: 36738094.
42. Dmuchowska DA, Pieklarz B, Konopinska J, et al. Impact of Three Waves of the COVID-19 Pandemic on the Rate of Elective Cataract Surgeries at a Tertiary Referral Center: A Polish Perspective. Int J Environ Res Public Health. 2021;18:8608. doi:10.3390/ijerph18168608
43. Nazar W, Niedoszytko M. Air Pollution in Poland: A 2022 Narrative Review with Focus on Respiratory Diseases. Int J Environ Res Public Health. 2022;19:895. doi:10.3390/ijerph19020895. PMID: 35055718.
44. Holnicki P, Tainio M, Kałuszko A, et al. Burden of Mortality and Disease Attributable to Multiple Air Pollutants in Warsaw, Poland. Int J Environ Res Public Health. 2017;14:1359. doi:10.3390/ijerph14111359. PMID: 29117145.
45. Zgłobicki W, Baran-Zgłobicka B. Air pollution in major Polish cities in the period 2005–2021: Intensity, effects and attempts to reduce it. Environ Res. 2024;240:117497. doi:10.1016/j.envres.2023.117497. PMID: 37914007.
46. Traczyk P, Gruszecka-Kosowska A. The Condition of Air Pollution in Kraków, Poland, in 2005–2020, with Health Risk Assessment. Int J Environ Res Public Health. 2020;17:6063. doi:10.3390/ijerph17176063. PMID: 32825405.
47. Cichowicz R, Dobrzański M. Impact of the size of settlement units, Covid-19 pandemic, and the ongoing war in Ukraine on air quality in Poland. Chemosphere. 2025;380:144442. doi:10.1016/j.chemosphere.2025.144442
48. Kobza J, Geremek M, Dul L. Characteristics of air quality and sources affecting high levels of PM10 and PM2.5 in Poland, Upper Silesia urban area. Environ Monit Assess. 2018;190:515. doi:10.1007/s10661-018-6797-x. PMID: 30109439.
49. Kryza M, Werner M, Holland M, et al. Quantifying the health impact of PM2.5 with various chemical transport models and for different years – A case study for Poland. Environ Int. 2024;194:109179. doi:10.1016/j.envint.2024.109179. PMID: 39667062.
50. Jagiełło P, Struzewska J, Jeleniewicz G, et al. Evaluation of the Effectiveness of the National Clean Air Programme in Terms of Health Impacts from Exposure to PM2.5 and NO2 Concentrations in Poland. Int J Environ Res Public Health. 2022;20:530. doi:10.3390/ijerph20010530