

## Research Article

# Air Pollution as an Emerging Risk Factor for Visual Health: Smog Related Ocular Pathologies

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## Abstract

Air pollution is now recognized as an important determinant of health on a global scale, although its effects on ocular morbidity remain under-investigated. The eye, being a directly vulnerable organ, is particularly susceptible to airborne toxins, especially pollutants of smog such as particulate matter (PM<sub>2.5</sub>), nitrogen oxides, sulfur dioxide, and ozone. This narrative review compiles evidence on the relationship between air pollution and ocular disease by synthesizing findings from epidemiological, clinical, and experimental studies published between 2010 and 2025. The results indicate that pollutants contribute to anterior segment disease, including dry eye disease, conjunctivitis, and blepharitis, exerting their main effects through oxidative stress, inflammation, and tear film instability. Long-term exposure to pollutants is clearly implicated in posterior segment pathology, such as glaucoma, retinal vascular dysfunction, and age-related macular degeneration, with mechanistic studies showing compromise of microvascular integrity and neurotoxicity. The risk is further aggravated by environmental determinants such as climate change and urbanization, while protective factors like residential greenness may mitigate adverse effects. Taken together, this body of evidence positions air pollution as an emerging risk factor for visual health, with implications for clinical practice, public health policy, and research. Addressing smog-related ocular pathologies requires interdisciplinary collaboration, standardized outcome measures, and inclusion of ocular health in environmental surveillance and prevention strategies.

**Keywords:** Air pollution; Smog; Ocular surface disease; Dry eye; Glaucoma; Retinal vascular dysfunction; Age-related macular degeneration; Visual health

## Introduction

Air pollution is now one of the most pressing health problems globally, and there is increasing evidence indicating the systemic and organ-specific diseases associated with ambient pollutants. While the respiratory and cardiovascular effects have traditionally been the primary focus, recent studies have also shifted attention to the eye as a sensitive target organ, which can suffer both acute and chronic damage due to exposure to smog [1,2]. The ocular system is a unique interface that allows airborne particulate matter (PM), nitrogen oxides (NO<sub>2</sub>), sulfur oxide (SO<sub>2</sub>), and ozone to exert a detrimental effect on the structures of the anterior and posterior segments [3,4].

The economic burden of air pollution on ocular health is multifaceted and includes diseases of the ocular surface, retinal vascular dysfunction, glaucoma, and age-related macular degeneration (AMD). Systematic reviews have shown that fine particulate matter (PM<sub>2.5</sub>) induces oxidative stress and inflammatory pathways in the corneal epithelial cells, which exacerbate risk factors for dry eye disease and conjunctival irritation [5,6]. These findings are further supported by clinical epidemiological studies, which demonstrate a strong correlation between PM<sub>2.5</sub> peaks and visits for ocular surface irritation and allergic conjunctivitis [7,8].

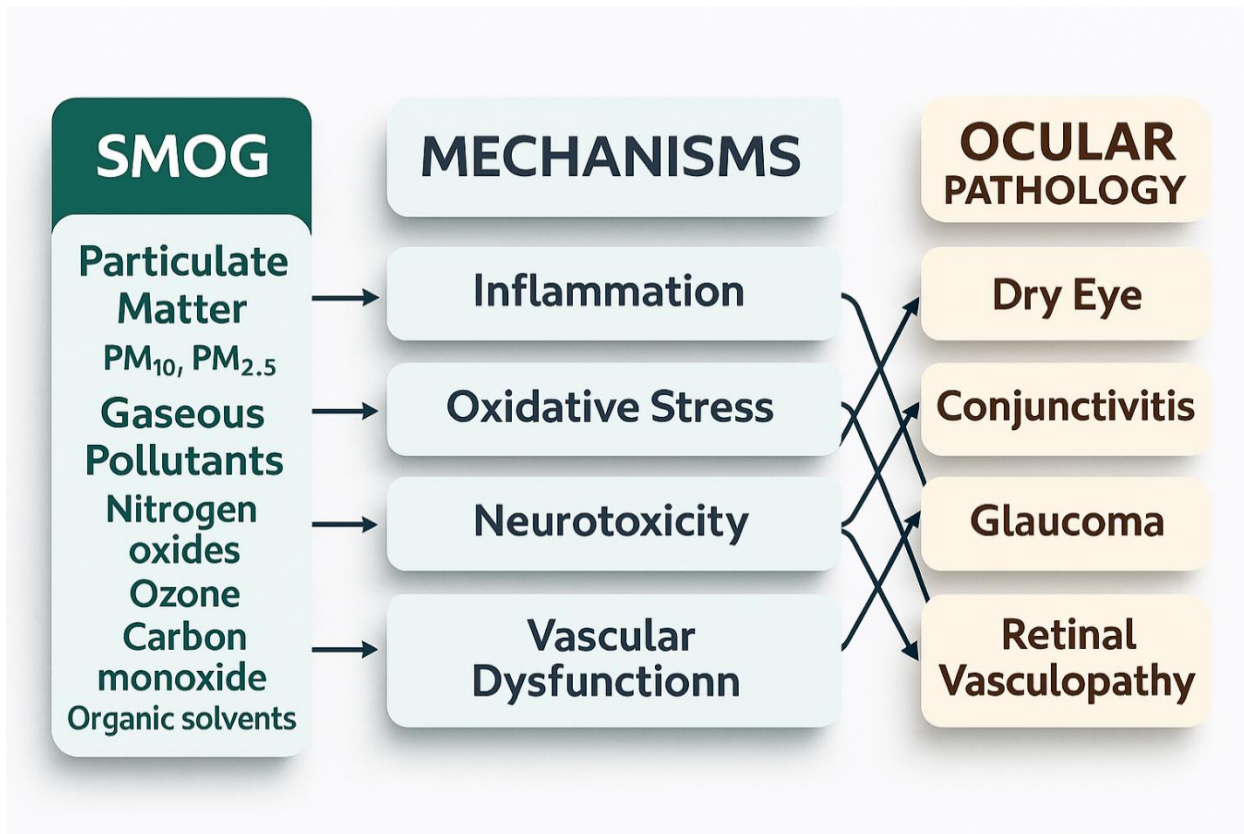
In addition to affecting the anterior segment of the eye, the posterior structures are also becoming a focus of pollution-related pathology. Recent reviews highlight that ambient pollutants, including PM<sub>2.5</sub>, NO<sub>2</sub>, and CO, are linked to glaucoma, AMD, and retinal vascular diseases, emphasizing the systemic exposure of the eye's microvasculature to inhaled toxins [9,10]. Meta-analyses have established that long-term exposure to PM<sub>2.5</sub> is associated with the accelerated development of visual impairments in both adults and children, suggesting that cumulative exposure can influence both developmental and degenerative processes in ocular tissues [4].

Preclinical and translational research is increasingly leveraged to understand the mechanistic foundations of these associations. Experimental models show that PM exposure leads to corneal epithelial inflammation, retinal microvascular dysfunction, and neural damage, which are mediated by oxidative stress and cytokine dysregulation [11,9]. These data align with clinical observations indicating higher rates of central retinal artery occlusion during periods of high smog and low ambient temperature, suggesting that meteorological factors play a supportive role in the exacerbation of pollutant toxicity [12].

Cohort studies and time series data from hospitals also provide valuable epidemiological evidence, showing an increased prevalence of dry eye disease and ocular surface irritation in areas with high PM<sub>2.5</sub> concentrations [6]. Geographic studies, including those in Chiang Mai, Thailand [13], reveal that the excessive ocular morbidity in populations residing in high-smog areas is disproportionately high.

Notably, air pollution does not act in isolation but is likely interdependent with other environmental factors, such as climate change and urbanization. The significance of climate-related increases in particulate matter levels and temperature fluctuations in relation to ocular infections and inflammatory conditions has been emphasized by narrative reviews, highlighting the growing burden of visual impairment in the most vulnerable populations [12]. Moreover, studies on residential greenness suggest that green spaces may mitigate some of the negative impacts of pollution on eye health, pointing to potential population-level interventions [14,1].

Together, these findings underscore the importance of considering air pollution as a significant and evolving threat to visual health. Smog-induced visual pathologies are an emerging concern for public health, influencing clinical practice, prevention strategies, and policy-making. This review aims to provide a comprehensive perspective on the relationship between air pollution and ocular health by synthesizing evidence on ocular surface disease, posterior segment pathology, and environmental determinants. In doing so, it highlights key gaps in current knowledge and outlines future research priorities, particularly in relation to the global processes of urbanization and climate change [3,11].



**Figure 1:** Air Pollution as an Emerging Risk for Visual Health

*“Diagram illustrating the causal pathway from smog pollutants to ocular diseases, mediated by biological mechanisms including oxidative stress, inflammation, neurotoxicity, and vascular dysfunction”*

### Background and Rationale

Air pollution is becoming a widespread health hazard of significance on the global spectrum, the effects of which are not limited to the respiratory system and heart but also ocular health. Being a directly exposed organ, the eye is exceptionally susceptible to the effects of air pollution (particulate matter (PM 2.5, PM 1.0), nitrogen oxides (NO<sub>2</sub>), sulfur dioxide (SO<sub>2</sub>), ozone, etc.), as it can trigger both acute irritation and the development of chronic diseases [1].

There is recent evidence of air pollution as a cause of ocular surface disease, in which pollutants cause the destabilization of tear films and initiate inflammatory reactions in cornea and conjunctiva [5]. The direct clinical impact of smog exposure is highlighted by the fact that hospital-based cohort studies have shown that the increase in PM 2.5 concentrations is linked with a rise in the incidence of diseases of the eyes, in addition to which dry eye disease is a substantial clinical burden [6]. Equally, epidemiological studies indicate that people living in smoggy areas have increased ocular surface irritation and allergic conjunctivitis [7].

Other ocular parts are also involved besides the anterior segment, including the posterior ocular structures. Glaucoma, retinal vascular malfunction, and age-related macular degeneration (AMD) have been associated with ambient pollutants, indicating that exposure to smog can contribute to degenerative changes involving ocular tissues [4]. The mechanistic studies also confirm that PM has the ability to cause retinal microvascular dysfunction through oxidative stress and endothelial injury, and this provides biological plausibility to these correlations [10].

Neurotoxicity of air pollution is also a possibility, and the reason is the hypothesis that long-term exposure to fine particulate matter can accelerate neural damage in ocular pathways, thus leading to progressive visual impairment [9]. This relevant issue is backed by longitudinal studies, which indicate that being exposed to PM<sub>2.5</sub> over an extended duration is associated with distorted optical pathways in children, which raises further concerns about developmental effects.

The risk is also aggravated by environmental factors like climate change since temperature variations and changes in the intensity of pollutants worsen ocular diseases and inflammation [12]. On the other hand, residential greenness literature indicates that environmental buffers can lessen some of the negative impacts of pollution on visual health, which is an indication of potential strategies to intervene in the sphere of public health [14].

A combination of these findings proves to frame air pollution as a new risk factor for visual health. The motivation behind such a narrative review was to combine scattered evidence on ocular surface disease, posterior segment pathology, and environmental determinants. The proposed review, through a critical examination of the existing literature, will offer an extensive framework for smog-related ocular pathologies comprehension and laying priorities for future research concerning global urbanization and climate change dynamics [3].

## Methods

This narrative review was undertaken with the aim of synthesizing the available evidence in the domain of the relationship between air pollution and ocular health, with particular emphasis on smog-related ocular pathologies. The comprehensive literature search was performed in databases such as PubMed, Scopus, Web of Science, and Google Scholar, and it included articles published since 2010. The search terms were Medical Subject Headings (MeSH), and the search combined these headings with keywords including: air pollution, particulate matter, smog, ocular surface disease, retinal pathology, glaucoma, age-related macular degeneration, and visual impairment. The search strategy was refined through the application of Boolean operators to ensure that relevant studies were included.

Articles were deemed eligible for inclusion if they reported empirical, clinical, or experimental evidence associated with ambient air pollutants, e.g., PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub>, SO<sub>2</sub>, ozone, or carbon monoxide, and ocular outcomes. Studies addressing both anterior and posterior segment conditions such as dry eye, conjunctivitis, glaucoma, retinal vascular dysfunction, and age-related macular degeneration were considered. Eligible designs included systematic reviews, meta-analyses, scoping reviews, narrative reviews, cohort studies, and experimental investigations, whereas non-peer-reviewed articles, editorials, and studies not explicitly focused on ocular health were excluded.

To identify relevant articles, an initial screening of titles and abstracts was conducted, followed by full-text review of potentially eligible studies. The search process involved removing duplicate records and hand-searching reference lists of key publications to locate additional sources. This iterative method ensured that both earlier and recent developments in the field were captured.

Extracted data included information pertinent to pollutant type, study design, ocular outcomes, and hypothesized mechanisms of damage, such as oxidative stress, inflammation, vascular dysfunction, and neurotoxicity. A thematic synthesis of findings was conducted, enabling integration of mechanistic insights with epidemiological and clinical evidence. This approach facilitated a structured account that highlighted both anterior and posterior segment pathologies, along with broader environmental determinants of ocular health.

Although narrative reviews do not employ formal risk-of-bias tools, methodological rigor was maintained by emphasizing systematic reviews, meta-analyses, and large-scale cohort studies. Preclinical evidence was incorporated to contextualize biological plausibility and critically assessed for translational relevance. As this study relied exclusively on published literature, ethical approval was not required; nevertheless, all sources were appropriately cited to ensure transparency and academic integrity.

## Results / Thematic Synthesis

**Ocular Surface Disease:** There is consistent evidence that air pollution exerts significant impacts on the anterior part of the eye, particularly the ocular surface. It is established that exposure to fine particulate matter (PM<sub>2.5</sub>) can disrupt tear film stability and trigger inflammatory responses in corneal epithelial cells, which predisposes individuals to the development of dry eye disease [5]. Cohort studies in hospitals confirm that peaks of PM<sub>2.5</sub> concentrations are strongly linked to increased cases of dry eye symptoms, and this evidence suggests that the clinical burden of smog is directly observable [6]. Epidemiological studies further show that people residing in areas with high levels of smog experience disproportionate cases of ocular surface irritation and allergic conjunctivitis [7]. Mechanistic support is provided by experimental studies, demonstrating that particulate matter induces oxidative stress and cytokine imbalance in ocular tissues, which underlies the clinical manifestations [11].

**Posterior Segment Disease:** The pathology of the posterior segments is also referred to as posterior segment ophthalmoscopy. Outside the ocular surface, the structures of the anterior segments are increasingly implicated in pollution-related pathology. PGS has been associated with PM<sub>2.5</sub> and NO<sub>2</sub>, and this evidence may indicate that smog exposure is a contributing factor in degenerative processes of ocular tissues [4]. Mechanistic research reveals that oxidative stress and endothelial damage caused by particulate matter lead to retinal microvascular dysfunction, which is biologically plausible to explain the associations [10]. Neurotoxicity has also been proposed, and chronic exposure to fine particulate matter has been suggested to accelerate neural damage in ocular pathways, thereby contributing to progressive visual impairment [9]. This concern is reinforced by longitudinal studies showing that prolonged exposure to PM<sub>2.5</sub> correlates with altered visual pathways in children, raising concerns about developmental effects.

**Environmental Determinants:** Climate change and urbanization also represent additional environmental factors that heighten the risk of pollution-related ocular disease. They are noted to exacerbate the effects of fluctuations in temperature and pollutant levels on ocular infections and inflammatory conditions, thereby increasing the burden of visual impairment in vulnerable groups [12]. Conversely, residential greenness studies suggest that environmental buffers may mitigate the negative impact of pollution on visual health, offering potential directions for population-level interventions [14]. The global relevance of this issue is supported by geographic research conducted in regions with high smog exposure, such as Chiang Mai, Thailand, which demonstrates unequal incidence of ocular morbidity among populations inhabiting polluted areas.

## Discussion

This narrative review has highlighted the expanding literature on air pollution as a cause of ocular morbidity, identifying the eye as a vulnerable organ system with direct exposure to environmental toxins. The literature synthesis demonstrates that both posterior and anterior ocular structures are affected by smog-related pollutants, with mechanisms involving oxidative stress, inflammation, vascular dysfunction, and neurotoxicity. These findings establish air pollution as a significant determinant of visual health, with implications for both individual well-being and societal burden.

The ocular surface disease evidence is particularly strong, as numerous cohort and hospital-based studies have confirmed the association between particulate matter peaks and elevated risk of dry eye disease, conjunctivitis, and allergic irritation [6]. Mechanistic studies provide biological plausibility, showing that PM<sub>2.5</sub> induces oxidative stress and cytokine dysregulation in corneal epithelial cells, which explains the observed clinical burden [11]. Much of the available evidence, however, is region-specific and concentrated in urban areas with high pollution levels, limiting generalizability to rural or low-exposure populations.

Posterior segment damage, including glaucoma, retinal vascular dysfunction, and age-related macular degeneration, is also implicated in pollution-related pathology. Epidemiological research demonstrates strong correlations between ambient pollutants and these degenerative conditions [4]. Mechanistic studies corroborate these findings, revealing that particulate matter disrupts retinal microvascular integrity and accelerates neurodegenerative processes [10]. However, heterogeneity in study designs, outcome measures, and exposure assessments complicates direct comparisons. Many studies rely on ecological or cross-sectional designs, which are less suitable for causal inference and may be confounded by socioeconomic or lifestyle factors.

The risk of pollution-related ocular disease is further amplified by environmental determinants such as climate change and urbanization. Reviews emphasize the role of temperature fluctuations and pollutant variability in exacerbating ocular infections and inflammatory conditions, thereby increasing the burden of visual impairment in vulnerable populations [12]. Conversely, residential greenness research suggests potential protective effects of environmental buffers, offering possible directions for preventive interventions [14]. These findings highlight the importance of considering environmental context when assessing ocular health outcomes, as pollutant exposure rarely occurs in isolation.

Despite the growing evidence base, several gaps remain. Longitudinal studies are limited, with few tracking long-term visual trajectories under sustained pollutant exposure. Standardized measures of ocular morbidity are lacking, hindering comparability across studies. Mechanistic pathways remain incompletely understood, particularly regarding interactions between oxidative stress, vascular dysfunction, and neurotoxicity in posterior segment disease. Addressing these gaps will require interdisciplinary collaboration across ophthalmology, environmental health, and molecular biology.

The implications are far-reaching for public health. With increasing pollutant exposure driven by urbanization and climate change, the incidence of smog-related ocular disease is expected to rise, especially in densely populated regions. Preventive strategies should extend beyond clinical management to include environmental measures such as emission reduction, expansion of urban greenness, and promotion of protective behaviors. Clinicians should also recognize environmental risk factors in diagnosis and treatment, as pollution exposure may exacerbate or accelerate disease progression.

This review confirms air pollution as a major emerging threat to visual health. It provides an evidence synthesis across ocular surface disease, posterior segment pathology, and environmental determinants to explain smog-related ocular conditions. Future research must prioritize longitudinal designs, standardized outcome measures, and mechanistic studies to strengthen causal inference and guide targeted interventions. Finally, integrating environmental health perspectives into ophthalmic research and practice will be essential to reduce the escalating burden of pollution-related visual impairment.

## Implications

The assembly of existing evidence underscores that air pollution cannot be regarded merely as an environmental nuisance; it is a significant risk factor for ocular morbidity. These findings carry implications for clinical practice, public health policy, and future research directions.

Clinically, there is a need to incorporate environmental exposures into the diagnosis and management of ocular disease by ophthalmologists and optometrists. The recognition that pathology of both anterior and posterior segments is influenced by particulate matter and gaseous pollutants implies that environmental risk factors should be included in patient history, alongside conventional determinants such as age, genetics, and lifestyle [4]. Ocular surface disease exacerbations and the progression of degenerative conditions can be reduced through preventive measures such as educating patients on minimizing exposure during high-smog periods and slowing disease development [5].

The evidence highlights the necessity of integrating environmental and health policies at the public health level. Populations living in urban areas, particularly those highly prone to smog, face disproportionate risks that may contribute to additional socioeconomic burdens [13]. Measures to reduce emissions, expand urban greenery, and monitor air quality could prevent ocular morbidity while simultaneously improving systemic health outcomes [14]. Furthermore, fluctuations in pollutant concentrations driven by climate change can intensify ocular infections and inflammatory pathology, requiring adaptive strategies in healthcare planning [12].

Regarding research implications, several priorities emerge. To establish causal relationships between prolonged pollutant exposure and visual decline, longitudinal studies are essential, particularly among vulnerable populations such as children and the elderly. Standardization of ocular outcome measures across epidemiological studies would enhance comparability and strengthen meta-analytical synthesis [1]. The interplay of oxidative stress, vascular dysfunction, and neurotoxicity in posterior segment disease should be further clarified through mechanistic investigations to guide targeted treatment interventions [9].

All of these implications confirm the urgency of conceptualizing air pollution as a determinant of visual health. The management of smog-related ocular pathologies must be multidisciplinary, involving collaboration among ophthalmology, environmental science, and public health. Stakeholders can mitigate the growing burden of pollution-related visual impairment and safeguard ocular health through policy reform, research innovation, and clinical vigilance in the context of global urbanization and climate change.

## Policy Implications

The evidence synthesized in this review underscores air pollution as a key determinant of ocular health, requiring policy responses that extend beyond conventional respiratory and cardiovascular paradigms. Although current air quality standards are primarily aimed at reducing systemic morbidity and mortality, the growing awareness of ocular pathologies associated with smog exposure provides strong justification for including visual health within environmental health policies [1].

Governments at the national level must ensure that air quality monitoring systems are strengthened to incorporate health indicators linked to ocular disease. Integrating ophthalmic outcomes into environmental monitoring would provide a more

comprehensive evaluation of pollution-related morbidity and enable targeted interventions [4]. Enforcement of policies to reduce emissions of fine particulate matter (PM<sub>2.5</sub>) and nitrogen oxides is particularly urgent, as these pollutants have been shown to contribute to both anterior and posterior segment ocular pathology [10].

At the urban planning level, ocular morbidity may be mitigated through strategies such as expanding residential greenery and reducing traffic-related emissions. Evidence supports that green spaces lessen the adverse visual health impacts of pollution, indicating that environmental design can serve as a viable public health intervention [14]. Ocular considerations within climate adaptation policies are also essential, as climate-driven fluctuations in pollutant concentrations exacerbate ocular infections and inflammatory conditions [12].

As part of healthcare policy, environmental risk assessment should be integrated into routine ophthalmic services. Public health campaigns can raise awareness of smog-related ocular hazards, encouraging preventive measures such as limiting outdoor activities during peak pollution hours and using protective eyewear. Moreover, healthcare systems in high-smog regions must anticipate increased demand for ophthalmic services and allocate resources accordingly [7].

Finally, visual health should be recognized as a subset of the global burden of disease attributable to air pollution. International cooperation is needed to establish standardized frameworks for monitoring, reporting, and mitigating pollution-related ocular morbidity. Such initiatives would align with sustainable development goals and strengthen the integration of environmental health and ophthalmology in global health agendas [3].

## Conclusions and Future Projections

This narrative review identifies air pollution as a major emerging threat to visual health. The synthesis of existing literature demonstrates that smog pollutants, particularly PM<sub>2.5</sub> and nitrogen oxides, are causative agents of a continuum of ocular diseases, including anterior segment disorders such as dry eye and conjunctivitis, and posterior segment conditions such as glaucoma, retinal vascular dysfunction, and age-related macular degeneration. Mechanistic studies provide biological plausibility, uncovering pathways of oxidative stress, inflammation, vascular compromise, and neurotoxicity that collectively contribute to the observed clinical burden.

The results emphasize that the health implications of air pollution must be reconceptualized to explicitly include ocular morbidity. Although respiratory and cardiovascular outcomes dominate environmental health discourse, the eye's unique susceptibility to airborne toxins warrants equal attention. For both clinical practice and public health planning, visual health should be identified as a critical component of the overall burden of disease due to pollution.

Future research should prioritize longitudinal designs to establish causation between prolonged pollutant exposure and progressive visual decline. Standardization of ocular outcome measures across epidemiological studies will enhance comparability and strengthen meta-analytical synthesis. Mechanistic investigations should further clarify the interactions of oxidative stress, vascular dysfunction, and neurotoxicity in posterior segment disease, thereby guiding targeted treatment interventions. Interdisciplinary collaboration among ophthalmology, environmental science, and public health will be essential for advancing this field.

Politically, the inclusion of ocular health in air quality standards and environmental monitoring frameworks will ensure more comprehensive evaluation of pollution-related morbidity. Urban planning that emphasizes green residential spaces and reduced traffic congestion can serve as protective measures against ocular disease. Public health campaigns should sensitize populations to the ocular risks of smog, promoting protective behaviors and timely medical care.

Air pollution represents an escalating threat to visual health in the context of urbanization and global climate change. This review synthesizes evidence across ocular surface disease, posterior segment pathology, and environmental determinants, setting priorities for future research. Addressing these challenges will require collaborative efforts across research, clinical practice, and policy, ultimately safeguarding ocular health in an increasingly polluted world.

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