Review

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Raja Saha , Sangita Maiti Dutta * , Madhumita Dubey

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Effects of Air Pollution on Birds: an Overview of the Consequences and Mitigation Strategies (Review)

Raja Saha [1], Madhumita Dubey [2] and Sangita Maiti Dutta [2,*]

[1] Biodiversity and Environmental Studies Research Centre, Midnapore City College, Kuturiya, Bhadutala, Paschim Medinipur, West Bengal 721129, India
[2] Assistant Professor, Department of Biological Sciences, Midnapore City College, Kuturiya, Bhadutala, Paschim Medinipur, West Bengal 721129, India
* Correspondence: smaitiduttazoo@gmail.com; Tel.: +91-79083-70081

Highlights

- Effects of air pollution on behavioural, physiological, and daily existence of birds.
- Overall idea about the pollution stress in birds.
- Overview of mitigation strategies against the pollution stresses.
- Highlighting the research gaps and scientific importance of the avian study.

Abstract

An increasing environmental concern, air pollution has a significant impact on biodiversity, including bird species. Because of their high metabolic rates, high levels of mobility, and direct exposure to the atmosphere, birds are especially susceptible to air pollutants. The current understanding of the effects of different air pollutants, including particulate matter, sulphur dioxide, nitrogen oxides, carbon monoxide, and ozone, on bird physiology, behaviour, reproduction, and survival is compiled in this review. The indirect impacts of pollution on avian food sources, habitat quality, and migration patterns are also covered. The review concludes by underscoring the necessity of more research on how birds react to complex pollutant mixtures and integrated conservation strategies.

Keywords: air pollution; birds; respiratory effects; reproductive toxicity; avian ecology; conservation

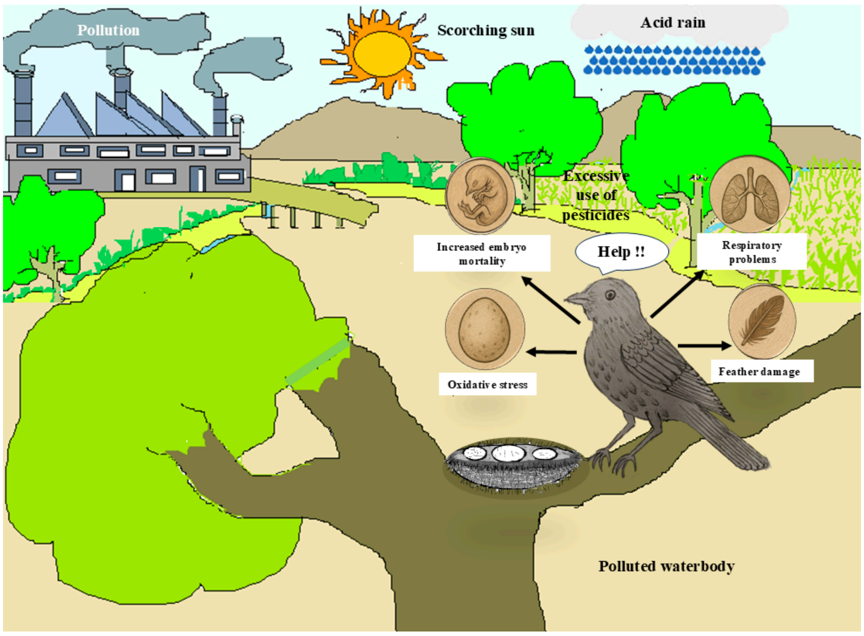

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Figure 1. Effects of air pollution on birds.

1. Introduction

Air pollution poses a mounting threat to global biodiversity, with birds serving as sensitive indicators of environmental degradation. Identifying pollutant sources enables targeted environmental policies and risk assessments for habitats critical to bird populations (Table 1). A recent meta-analysis by Smith et al. (2023) published in Ecological Indicators compiled over 150 avian studies and confirmed significant correlations between air quality indices and bird abundance, diversity, and breeding success, highlighting the role of birds as frontline indicators of ecosystem health. This review synthesizes recent findings with some foundational studies to provide continuity in emerging research themes on how air pollutants such as particulate matter (PM2.5, PM10), nitrogen oxides (NOx), ozone (O3), and heavy metals impact avian physiology, behaviour, reproduction, migration, and communication. Understanding avian responses to pollution provides early insights into ecosystem collapse and can serve as a benchmark for broader conservation efforts (Şekercioğlu et al. 2023). This review compiles and analyzes recent global studies on avian responses to air pollutants, with a focus on unique physiological, behavioural, reproductive, and aerodynamic consequences. The article also highlights alterations in aerodynamics and navigation due to pollution exposure and assesses conservation and mitigation strategies.

Table 1. Types of Air Pollutants Impacting Birds.

Pollutant	Source	Effect on Birds	Reference
Particulate Matter (PM2.5, PM10)	Combustion, industrial dust	Respiratory inflammation, lung damage	Barton et al. 2023
Nitrogen Oxides (NOx), Sulfur Dioxide (SO_2)	Vehicle exhaust, power plants	Acid rain, immune suppression	Richard et al. 2024
Ozone (O_3)	Secondary pollutant from NOx + VOCs	Lung lesions, reduced foraging	Sanderfoot et al. 2017
Heavy Metals (Pb, Hg, Cd, Zn)	Smelting, fuel combustion	Neurotoxicity, reproductive damage	Borghesi et al. 2016
Microplastics & VOCs	Urban dust, tire wear	Lung blockage, endocrine disruption	Johannessen et al. 2022

2. Sources and Types of Air Pollutants Affecting Birds

2.1. Respiratory Effects

In addition to having impaired lung function, birds exposed to high gas and particulate matter concentrations show histopathological damage to their respiratory tissues (Sanderfoot et al. 2017). Fine particles can overload the respiratory systems of birds, resulting in respiratory stress and inflammation. In urban China, birds exposed to PM2.5 exhibited increased macrophage infiltration and decreased lung volume (Zhang et al. 2025). 51 bird species had an average of 416 microplastic particles per gramme in their lungs, according to a study conducted in the Chengdu region of China. Polyethylene (PE), polyvinyl chloride (PVC), and tyre fragments were among the plastics, suggesting inhalation as a primary exposure pathway. Inhaled pollutants produce reactive oxygen species (ROS), which damage cells and tissues while overwhelming antioxidant defences. Sulphur dioxide (SO_2), nitrogen oxides (NOx), and ozone (O_3) cause lung damage and oxidative stress. Reduced erythrocyte counts and oxidative stress markers in feral pigeons have been associated with NOx inhalation (Salmón et al., 2018) (Figure 2).

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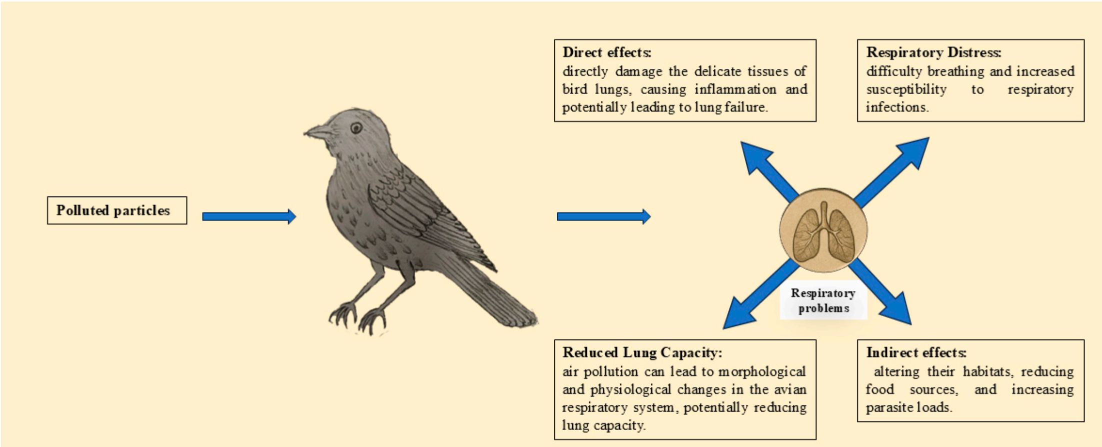

Figure 2. Effects of air pollution on respiratory system in birds.

2.2. Physiological Effects

Industrial operations and the burning of fossil fuels release metals like lead, cadmium, and mercury into the atmosphere (Kumar et al. 2025). These could infiltrate feathers and tissues, affecting the neurological and reproductive systems. Due to proximity to smelters, royal spoonbill blood lead levels in Colombia surpassed 210 µg/L (Bjedov et al., 2024). Egret feathers from wetlands in Bhubaneswar, India, had high levels of Zn (84 µg/g) and Cu (15.6 µg/g) (Tyagi et al. 2020). The immunity of house sparrows from high-ozone regions of Mexico was compromised by their lower natural antibody titres (Salaberria et al. 2023). In-depth physiological analysis identifies pollution's less-lethal impacts, which helps identify environmental stress in bird populations early. Limited long-term research linking the length of exposure to pollutants to immunological and biochemical alterations. A lack of information regarding the genetic consequences and intergenerational effects of prolonged exposure to pollutants.

2.3. Behavioural Effects and Endocrine Disfunction

Volatile organic compounds may affect endocrine function and bird behaviour (Ottinger et al. 2008). Exposure to heavy metals and volatile organic compounds can impair one's ability to navigate, think clearly, and avoid predators (Table 2). Ozone hinders forest birds' ability to defend their territory and attract mates by reducing their singing behaviour (Condolin et al. 2019). Decreases in migratory warbler populations throughout North America are correlated with ozone pollution (Liang et al. 2020). Exposure to heavy metals and microplastics has changed the timing of migration, causing delays in departures and a rise in confusion. The local extinction of delicate insectivorous birds in urban settings is associated with air pollution in Europe (Morelli et al. 2023). In susceptible passerines, prolonged exposure has been associated with diminished cognitive abilities, tremors, and even death. Behavioural plasticity provides non-invasive markers of environmental impact by reflecting stress or adaptation in real time (Caizergues et al. 2022). Setting priorities for conservation resources and tactics is aided by the differentiation of species-specific vulnerabilities. Preserving biodiversity in the face of increasing urbanisation requires converting research into workable conservation frameworks (Marzluff et al. 2008). supports the creation of policies and environmental education by offering a comprehensive and current understanding of how air pollution affects birds and inability to evaluate sub-lethal pollutant impacts across a variety of bird species using standardised behavioural metrics. Very few databases are available for regionally endemic and lesser-known species in developing nations and inadequate evaluation of these interventions' scalability and long-term efficacy.

Table 2. Behavioural Changes by Pollutant.

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Behaviour	Pollutant(s)	Effect	Reference
Foraging	PM2.5, SO_2	Reduced activity, disorientation	Singha et al. 2024
Mating	NOx, PM10	Reduced courtship, mating calls	Onyeabor et al. 2024
Migration	O_3, CO_2, PM	Route shift, delay, energy loss	Rio et al. 2024
Nesting	PM, VOCs	Higher, riskier nest sites; poor materials	Barton et al. 2023
Aggression/Stress	O_3, heavy metals	Higher agitation, anxiety	Relić et al. 2023
Parental care	O_3, Pb, NO_2	Less feeding, more abandonment	Borghesi et al. 2016
Flocking	PM, noise	Disorganized flocks, social breakdown	Barton et al. 2023

2.4. Effects on Migration and Aerodynamics

Barton et al. (2023) demonstrates that air pollution is increasingly interfering with migration patterns, both spatially and temporally. Jat et al. (2021) found that increases in PM2.5 levels above 120 μg/m³ pushed bar-headed geese and Arctic terns to veer up to 250–320 km from their usual migratory routes across the Indo-Gangetic Plain. According to a Ross, 2023 and his East Asia Flyway Consortium study, the average arrival times of barn swallows across Chinese monitoring stations were also 14% later. Long-distance migrants experience increased metabolic strain and decreased survival as a result of the energetic cost of flight rising under pollution stress due to compromised respiratory efficiency and altered thermoregulation (Hedenström et al. 2024). The survival of species and the flow of genetic material depend on migration. Disruptions can affect biodiversity and ecosystems in a cascade of ways (Table 3). Research on the effects of air pollution on wingbeat dynamics and flight muscle performance is limited and need more research work on it.

Table 3. Air Pollution Disrupts Avian Aerodynamics.

Pollution Type	Aerodynamic Effect	Biological Impact	reference
Particulate Matter (PM2.5, dust, soot)	Deposits on feathers increase drag, reduce lift	More energy spent during flight, increased fatigue	Zhang et al. 2021
Heavy Metals (Pb, Hg)	Neurotoxicity affects neuromuscular control of wings	Impaired flight coordination and stability	Rutkiewicz et al. 2012
Volatile Organic Compounds (VOCs)	Damage feather keratin and reduce waterproofing	Impaired insulation and flight in birds	Alves Soares et al. 2024
Microplastics (airborne fibres)	Embed in feather barbs	Disrupts aerodynamic feather alignment	Fuller, 2015
Ozone (O_3)	Causes oxidative stress on wing muscles	Weakened power stroke and manoeuvrability	Yap, 2018

2.5. Reproductive Effects

Since population sustainability depends on reproductive success, it is essential for species conservation to comprehend how pollution affects reproductive decline. By imitating or blocking hormones, pollutants can disrupt growth, the stress response, and reproduction (Coppock et al. 2022). Polluted environments have been shown to have lower fledgling survival, thinner eggshells, and lower hatching success. Reduced clutch size, eggshell thinning, and decreased fertility are all linked to heavy metals like Pb and Hg (Mora, 2003). Acid rain, which comes from SO_2 and NOx, causes soil to become more acidic, which lowers the amount of calcium available for healthy eggshells (Graveland, 1998). Pollutants can alter the way parents raise and care for their young, which may further impact the development of the offspring (Grace et al. 2024). Hormonal imbalances brought on by pollutants like dioxins and polychlorinated biphenyls (PCB) can have an impact on reproductive physiology (Coppock et al. 2022) (Table 4).

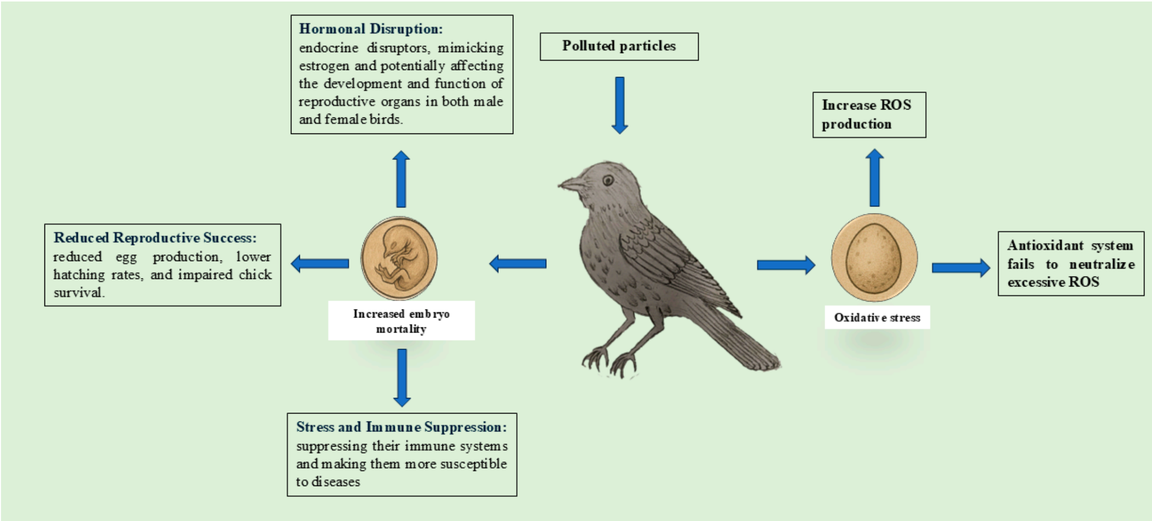

Figure 3. Effects of air pollution on Reproductive and oxidative stress in birds.

Table 4. Reproductive effects of pollutants.

Pollutant	Reproductive Impact	Example	Reference
PM2.5 / Soot	Hormonal imbalance, embryo toxicity	Magpies (China, 2023)	Saleem et al. 2024
NOx & SO_2	Delayed ovulation, low mating success	Great tits (France, 2023)	Saulnier et al. 2023
Heavy metals (Pb, Cd)	Thin shells, deformities	Tree swallows (USA, 2022)	Espín et al. 2024
VOCs / O_3	Oxidative stress in ovaries/testes	Pigeons (India, 2024)	Madhu et al. 2022
Microplastics	Hormonal interference	Egrets in coastal Taiwan (2024)	Grace et al. 2022

2.6. Effects on Communication and Vocalization

Pollution impacts communication by causing avian mating calls to become less complex, loud, and frequent (Condolin et al. 2019). In impacted bird populations, these acoustic disturbances can reduce reproductive success and destabilise community structure by harming territorial defence, modifying social hierarchies, and affecting mate attraction. Pollutants that are both acoustic and chemical disrupt vocal signals (Brumm et al. 2013). In Germany, urban blackbirds exposed to nitrogen oxide showed a 25% reduction in the volume of their dawn chorus (Iqbal, 2024). This reduction may result in a lower rate of successful reproduction and weakened territorial defence since it probably affects mate attraction and territory establishment, both of which rely significantly on vocal cues. Social organisation and reproduction depend on acoustic communication (Yadav et al. 2024). Population dynamics and mating success are at risk due to disturbances. Because of acoustic communication systems are not well understood in relation to the combined effects of noise and chemical pollution (Table 5).

Table 5. Communication disruption by pollutions.

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Pollution Type	Communication Effect	Example	Reference
PM2.5 / O_3 / NOx	Reduces song quality, affects brain centres	UK starlings (2023)	Binner et al. 2017
Heavy metals	Affects song learning, memory	Canadian sparrows (2024)	Giovanetti et al. 2024
VOCs	Delays vocal development in chicks	India (2023)	Kannan et al. 2025
Urban noise	Causes acoustic masking, vocal fatigue	Germany (2024)	Briseño-Jaramillo et al. 2025
Haze/soot	Obscures plumage signals	Thailand doves (2023)	Robson et al. 2020

2.7. Effects on Food Habitat, Migration, and Population

The availability of fruits, seeds, and insects is reduced as a result of vegetation changes brought on by air pollution.

Bird song complexity and activity were reduced by 15% for days after exposure to wildfire smoke (Sanderfoot et al. 2024). Acid rain is a byproduct of SO_2 and NOx that changes aquatic food webs, affecting water birds that rely on fish and invertebrates (Richard et al. 2024). Wading and diving birds have less access to aquatic food due to increased eutrophication caused by nitrogen deposition (Ngatia et al. 2019) and excessive use of pesticides in fields (Saha et al. 2024; Sanyal et al. 2024). Degraded habitats have fewer nesting sites and increased susceptibility to predators. Insect and plant diversity are reduced in polluted habitats (Saha et al. 2025), which also reduces food sources and nesting materials. Because pollutants interfere with orientation and magnetoreception, they can cause disruptions to migration routes (Wiltschko et al. 2023). Long-term exposure may lead to population declines in urban and industrial areas (Kekkonen, 2017). Long-term changes in community composition have been observed in high-pollution areas. Elevated levels of heavy metals in urban birds' feathers and blood samples, including sparrows and pigeons (Asgari et al. 2024). Forest birds in North America and Europe have declined in sensitive species in regions with elevated NOx and O_3 levels (Reif et al. 2023). Birds in coal mining regions like China and India have high mortality, decreased diversity, and obvious respiratory distress (Cortes-Ramirez et al. 2018). But, The dispersion of pollutants across migratory corridors and nesting habitats has not been fine-scale mapped. According to a recent study by Barton et al. (2023), avian health can act as an early warning system for human exposure to air pollutants because bird population declines are correlated with an increase in respiratory illnesses in urban areas.

3. Levels of Effects of Air Pollution on Bird Species

According to the Kekkonen (2017), the most affected species include European starlings, house sparrows, and rock pigeons, which show significant pollution-related effects such as heavy metal bioaccumulation, song disturbance, and infertility. For example, a study in Beijing in 2023 found that house sparrows had blood lead levels 30% higher than those in suburban areas, and starlings nesting near roads had a 40% lower chance of successfully launching their young (Shang et al. 2023). Swallows, black kites, and great tits, show measurable but varying effects, such as delayed migration, altered plumage quality, and weakened immune systems. Arrivals of barn swallows at Chinese monitoring stations were delayed by 14%, according to Mitchell et al. (2024). Resilient species such as crows, rose-ringed parakeets, and cattle egrets display adaptive behaviour, such as flexible

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foraging and urban nesting, with minimal physiological impact, despite the presence of subtle stress markers (such as elevated corticosterone) in some urban populations (Chitty et al. 2024) (Table 6a–c).

Table 6. (**a**): Highly Affected Species. (**b**): Moderately Affected Species. (**c**): Minimally Affected / Resilient Species.

Species	**Region**	**Key Impacts**	**Reference**
House Sparrow (*Passer domesticus*)	India, China	Oxidative stress, low reproductive success, reduced song activity	Mahata et al. 2023
Rock Pigeon (*Columba livia*)	Urban centers globally	High Pb and Cd accumulation, behavioural anxiety, egg deformities	Bala et al. 2020
European Starling (*Sturnus vulgaris*)	UK, Poland	Decreased song complexity, neurotoxicity, reduced clutch size	Kucharska, 2023
Common Myna (*Acridotheres tristis*)	South Asia	Delayed breeding, altered foraging behaviour	Magory Cohen et al. 2021
Tree Swallow (*Tachycineta bicolor*)	USA	Shell thinning, embryonic mortality, altered flight	Coppock et al. 2022
Species	**Region**	**Key Impacts**	**Reference**
Great Tit (*Parus major*)	Europe	Changes in song patterns, delayed hatching, immune suppression	Kubacka et al. 2024
Barn Swallow (*Hirundo rustica*)	Spain, Turkey	Route shifts in migration, altered plumage brightness	Lombardo et al. 2022
Black Kite (*Milvus migrans*)	India	High heavy metal load, mild reproductive suppression	Katzner et al. 2024
Nightjar (*Caprimulgus europaeus*)	UK	Decreased nocturnal activity under ozone peaks	Mitchell, 2019
Laughing Dove (*Spilopelia senegalensis*)	Africa, Middle East	Nesting changes, reduced body mass	Kopij, 2023
Species	**Region**	**Key Impacts**	**Reference**
Cattle Egret (*Bubulcus ibis*)	Global tropics	Minor shifts in nesting behaviour	Abdullah et al. 2017
House Crow (*Corvus splendens*)	Asia	Short-term stress response, adaptive foraging	Alamshah, 2024
Feral Parakeet (*Psittacula krameri*)	Europe, India	No major reproduction issues in smog zones	Rahmani, 2022

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4. Conservation and Mitigation Strategies

Air quality sensors are being installed in urban green spaces, wetlands, forests, and migratory stopovers (Raihan, 2023). Over 50 protected areas have ozone and PM2.5 monitors integrated by the German Federal Agency for Nature Conservation (Petry et al. 2020). According to Salmón et al. (2018) a negative correlation between Eurasian blackbirds' (*Turdus merula*) nesting success and elevated ozone levels. Permits early conservation measures and risk assessment in real time for vulnerable bird populations (Battisti et al. 2023). Creation of tree corridors, vertical gardens, and green belts to improve air quality and lower pollution levels close to bird habitats. According to a 2023 study conducted in Ahmedabad, India, urban parks with a lot of trees lowered PM2.5 levels by 37%, which was good for local bird species like bulbuls and tailorbirds (Suhane et al. 2023). Utilisation of indigenous plant species with a high capacity to absorb pollutants and draw birds (e.g., *Ficus benghalensis*, *Azadirachta indica*) (Roy et al. 2020). In addition to serving as pollutant sinks, wetlands offer bird breeding and feeding grounds. Heavy metal concentrations in sediments were lowered by up to 60% through wetland restoration projects that used artificial floating wetlands, allowing spoonbills, herons, and ibises to recolonise (Pandiyan et al. 2023). Collisions with illuminated structures are the cause of many migratory bird deaths. "Lights Out" programs provide a solution to this issue (Kenney, 2015). The initiative's participating skyscrapers reported a 60% decrease in collisions between birds and buildings during spring migration (Lomery, 2020). Efficiency of mating and alarm calling is decreased. Sound-absorbing vegetation installation and construction activity control during nesting seasons (Bošnjaković et al. 2024). In the vicinity of Ramsar wetlands, India, the Central Pollution Control Board (CPCB) implemented more stringent SO_2 and NOx emission limits in 2024 (Mathew et al. 2025). The air quality index (AQI) improved by 20% and the number of migratory birds, such as ruddy shelducks and northern pintails, increased after enforcement around Chilika Lake, for instance, according to satellite and field monitoring (Muduli et al. 2024). The heavy metal or particulate load is measured by routinely sampling birds such as pigeons, egrets, and crows. Heavy metal monitoring using feathers is inexpensive, scalable, and non-invasive. The "Air Safe Birds" project, which Bird Life International started in Southeast Asia in 2023 and involved over 30,000 citizen-reported entries, identified bird absence hotspots close to heavily polluted roads (Tan et al. 2023). Local governments use the data to plan low-emission times or reroute traffic around important bird areas.

5. Discussion

Globally, air pollution poses a serious but frequently disregarded threat to bird populations. Large-scale changes in community structure and migration patterns are among its effects, as are respiratory and reproductive impairments. For avian biodiversity to survive in an increasingly industrialised world, effective conservation initiatives must combine habitat preservation and pollution control (Kolawole et al. 2023). The success of current models like Singapore, New York, and Chilika suggests that science-driven, participatory conservation is not only feasible but effective. However, scaling these models, particularly in the Global South, remains a priority for global avian conservation. These strategies showcase a multidisciplinary approach, combining ecology, technology, urban planning, and community engagement to address the air pollution crisis affecting birds. Air pollution's impact on reproduction is one of the most critical and underappreciated factors contributing to bird population declines (Barton et al. 2023). It not only reduces individual fitness but threatens species viability over time. Protecting avian reproductive health should be central in policy, monitoring, and mitigation strategies. Bird communication is essential for survival and reproduction (Podos et al. 2022). Air pollution, both directly and indirectly, compromises the acoustic and visual signals birds depend on (Passarotto et al. 2025). This leads to disrupted mating, reduced fitness, and ecological imbalance. Understanding and mitigating these impacts through acoustic monitoring, policy changes, and habitat design is crucial for bird conservation in an increasingly polluted world. Air pollution reshapes the behaviour of birds in profound ways, often reducing their ability to survive, reproduce, and thrive. These behavioural shifts especially in foraging, nesting, mating, and migration are early ecological warning signals (Saha et al. 2025). Addressing them requires urgent mitigation of air pollution, continued behavioural monitoring, and integration of avian ethology into environmental policy.

6. Conclusions

The study of air pollution effects on birds is not only scientifically and ecologically crucial but also urgent. With rising urbanization, industrial output, and anthropogenic emissions, understanding avian responses helps protect ecosystem health, biodiversity integrity, and ultimately, human well-being. This research lays the groundwork for adaptive environmental management and conservation strategies tailored to emerging pollution threats in both global and local contexts. Longitudinal studies tracking pollutant exposure and reproductive success over generations. Species-specific sensitivity profiling, especially for migratory and apex species. Integrated pollution assessments, combining air, water, plastic, noise, and light stressors. Biomarker development, such as microplastic counts, stress hormones, and feather colour metrics. This review demonstrates the multifaceted impacts of air pollution on avifauna and underscores the necessity of integrative, data-driven approaches to conserve birds in polluted habitats. As air quality continues to decline globally, understanding and mitigating its effects on bird populations is not only essential for biodiversity conservation but also for ensuring ecological balance and sustainability.

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