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Electromagnetic Radiation Exposure and its Biological Hazards on Avian Species: A Critical Review

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Abstract: Birds are increasingly exposed to man-made electromagnetic radiation (EMR) due to rapid growth in wireless communication technologies, including mobile networks, broadcast antennas, and satellite systems. Exposure to radiofrequency (RF) EMR has raised global concern regarding its potential harmful effects on avian species, particularly in urban and suburban ecosystems where antenna density is high. Birds possess lightweight body structures, high metabolic rates, and magnetoreception capabilities, making them especially sensitive to electromagnetic fields. Emerging evidence indicates that EMR may disrupt navigation behavior, impair reproductive success, and induce physiological stress in various bird species. Structural and functional alterations in cells, increased oxidative stress, DNA damage, and reduced fertility have been observed under chronic exposure conditions. Additionally, EMR absorption leads to thermal effects in tissues, quantified as Specific Absorption Rate (SAR), which may cause heating of small organs such as the brain and reproductive organs due to their compact body size. Studies have reported declines in bird populations in regions with dense telecommunication infrastructure, along with behavioral changes such as disorientation, nest desertion, and altered vocalization patterns. However, knowledge gaps remain concerning frequency-dependent biological interactions, long-term ecological consequences, and combined exposure from multiple radiation sources. This review highlights the current scientific understanding of EMR-induced hazards to birds, emphasizing mechanistic pathways, species-specific vulnerabilities, and environmental risk factors. The study advocates for precautionary measures, optimized antenna installation policies, and continued research to protect avian biodiversity amid expanding wireless connectivity.

Keywords: *Electromagnetic Radiation, Birds, SAR, Magnetoreception, Reproductive Toxicity, Avian Behavior, Biodiversity Decline.*

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I. INTRODUCTION

Birds play a crucial role in maintaining ecological balance through pollination, seed dispersal, and pest regulation. Although, over the last few decades, there has been increasing concern about the possible impact of anthropogenic electromagnetic radiation (EMR) on avian populations (Balmori, 2009; Cucurachi et al., 2013). The rise in mobile communication, satellite navigation, Wi-Fi networks, and, most recently, 5G infrastructure has resulted in a continuous increase in environmental electromagnetic exposure. Consequently, bird species are now exposed to radiofrequency electromagnetic fields (RF-EMFs) of varying intensities and frequencies throughout their habitats (Bandara & Carpenter, 2018).EMR, particularly in the radiofrequency and microwave range (from 300 MHz to 300 GHz), interacts with biological systems through both thermal and non-thermal mechanisms (Hardell & Carlberg, 2020). While thermal effects involve tissue heating and energy absorption, non-thermal effects include oxidative stress, DNA damage, and disruptions in cellular communication and circadian regulation (Panagopoulos et al., 2015). Birds, due to their small body size, high metabolic rate, and reliance on magnetoreception for navigation, are considered particularly vulnerable to EMR exposure (Engels et al., 2014; Ritz et al., 2004). The laboratory studies have shown that weak electromagnetic fields (MHz range) can interfere with the magnetic compass orientation in migratory birds such as European robins (*Erithacus rubecula*) (Wiltschko et al., 2015).Several field studies across Europe and Asia have reported changes in bird behavior, nest density, and reproductive success near mobile phone base stations (Balmori, 2010; Everaert & Bauwens, 2007). For instance, a reduction in the population density of sparrows (*Passer*

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domesticus) has been observed in urban regions with high EMR intensity compared to rural areas (Balmori & Hallberg, 2007). Similarly, observations indicate altered breeding cycles, decreased clutch size, and increased oxidative stress markers in birds exposed to chronic electromagnetic fields (Cucurachi et al., 2013). Despite such evidence, the data remain heterogeneous, partly due to differences in methodologies, exposure assessment, and ecological variability. With the introduction of 5G technology, new frequencies (particularly in the millimeter-wave band, 24–100 GHz) and denser network infrastructure have emerged (Russell, 2018). These high-frequency signals have shorter wavelengths and different propagation characteristics, which may lead to localized hotspots of radiation exposure in both urban and peri-urban environments. Birds perching on antenna masts or nesting near transmitters could therefore experience higher localized Specific Absorption Rates (SARs). However, field-based quantitative studies on EMR exposure and biological effects in free-living birds remain limited. The geographic information system (GIS) and spatial interpolation methods now provide promising tools to assess EMR distribution in complex terrains and to model exposure gradients in relation to bird habitats (Kumar et al., 2023). Integrating these spatial tools with ecological and physiological datasets could help quantify dose–response relationships more accurately. In this context, the present review critically evaluates the current knowledge on EMR exposure and its biological hazards on avian species. It aims to: (i) synthesize experimental and field-based evidence, (ii) discuss potential biophysical mechanisms underlying observed effects, (iii) highlight methodological gaps and uncertainties, and (iv) suggest directions for future interdisciplinary research to assess the ecological risks posed by the expanding EMR environment.

II. SOURCES AND MEASUREMENT OF EMR IN AVIAN HABITATS

Avian habitats in both natural and human-modified environments are increasingly exposed to a wide spectrum of electromagnetic radiation (EMR). These sources originate from both natural geophysical processes and a rapidly growing range of anthropogenic wireless communication technologies (Bandara & Carpenter, 2018). Effective assessment of EMR exposure among bird populations requires an understanding of these emission sources as well as the instrumentation and spatial techniques used for measurement.

➢ *Sources of EMR in Avian Habitats:*

- *Natural Sources:*

Natural electromagnetic fields are generated by terrestrial and cosmic processes, including:

✓ Solar radiation, across ultraviolet (UV), visible, and infrared wavelengths.
✓ Earth's geomagnetic field, essential for magnetoreception in migratory birds (Ritz et al., 2004).
✓ Atmospheric events, such as lightning that produces extremely low frequency (ELF) emissions.

Birds have evolved in the presence of these natural fields and depend on geomagnetic cues for orientation and navigation during migration (Wiltschko et al., 2015).

- *Anthropogenic Sources:*

The rapid expansion of communication infrastructure has introduced widespread artificial radiation exposures, notably:

✓ Mobile base stations for 2G–5G networks
✓ Mobile phones, Wi-Fi, and Bluetooth transmitters
✓ Radio and television broadcast towers
✓ Radar and satellite communication systems **(**Russell, 2018**)**
✓ Internet-of-Things (IoT) infrastructure

In urban ecosystems, birds roosting on antenna structures, street poles, and building rooftops encounter high-intensity EMR hotspots (Everaert & Bauwens, 2007).With 5G networks, millimetre-wave (mmWave) transmissions (24–100 GHz) require dense deployment of small cells, altering near-field exposure profiles (Hardell & Carlberg, 2020). This shift raises concerns regarding SAR (specific absorption rate) accumulation in small bird species perched close to antennas.

➢ *Measurement Techniques for EMR Exposure in Avian Habitats:*

Monitoring EMR around bird habitats typically involves:

- *Broadband Survey Meters:*

Portable RF meters capable of measuring the total field strength across a wide frequency range (Sub-MHz to 40+ GHz), useful for near-tower and nesting site exposure assessments (Kumar et al., 2023).

- *Frequency-Selective Measurement Systems:*

Spectrum analyzers with isotropic probes allow frequency-resolved exposure profiling**,** essential in multi-signal environments with overlapping network services.

- *SAR Estimation Models:*

Biophysical computational tools estimate EMR absorption in avian tissues based on:

✓ Dielectric properties
✓ Body size and geometry
✓ Incident field strength

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Table 1 Estimated SAR Values in Avian Habitats Exposed to EMR

Bird Species	Habitat type	Frequency (MHz/GHz)	Electric Field Strength (V/m	Estimated SAR (W/kg)	References
House Sparrow (*Passer domesticus*)	Urban rooftop	900 MHz	5-10	0.2-0.5	Everaert & Bauwens, 2007
Pigeon (*Columba livia*)	Urban park	1800 MHz	2-6	0.1-0.4	Cucurachi et al., 2013
European Robin (*Erithacus rubecula*)	Suburban forest	900 MHz	1-3	0.5-0.15	Engels et al., 2014
House Sparrow (*Passer domesticus*)	Rural farmlands	1800 MHz	0.5-1.5	0.01-0.05	Balmori, 2010
Migratory Songbirds	Wetlands/migration stopover	2.4 GHz	0.2-1	0.005-0.02	Ritz et al., 2004
Small Passerines (general)	Near 5G small cells	28 GHz (mm Wave)	1-3	0.02-0.1	Hardell & Carlberg, 2020

➢ *GIS and Spatial Interpolation for Exposure Mapping:*

Advances in geospatial analysis enable spatial prediction of EMR patterns across diverse terrains:

- GIS-based modeling links EMR levels with bird nesting and migration data.
- Spatial interpolation techniques such as Inverse Distance Weighting (IDW) and Kriging generate continuous exposure maps from point measurements (Kumar et al., 2023).
- These tools are critical in identifying urban–rural exposure gradients, ecological risk zones, and long-term spatial changes.

III. BIOLOGICAL MECHANISMS OF ELECTROMAGNETIC RADIATION EFFECTS IN BIRDS

Electromagnetic radiation (EMR) can influence avian biological systems through multiple interrelated mechanisms. These effects broadly include oxidative stress, disruption of magnetoreception, reproductive toxicity, and behavioral changes. The degree of impact depends on exposure frequency, field intensity, duration, and proximity to communication infrastructure (Cucurachi et al., 2013).

➢ *Oxidative Stress and Cellular Impairment:*

RF-EMF can disrupt cellular homeostasis and induce overproduction of reactive oxygen species (ROS) in biological tissues (Panagopoulos et al., 2015). Excessive ROS generation:

- Damages DNA, lipids, and proteins
- Reduces antioxidant enzyme levels
- Increases apoptosis and inflammatory responses

Experimental studies have shown increased oxidative markers in birds exposed to chronic EMR, indicating that non-thermal mechanisms contribute to biological stress (Hardell & Carlberg, 2020).

➢ *Magnetoreception Interference:*

Many migratory bird species depend on the Earth's geomagnetic field for navigation. RF exposure can disrupt this sensory mechanism by interacting with cryptochrome photoreceptors in the retina (Ritz et al., 2004; Wiltschko et al., 2015). Even weak electromagnetic noise in urban environments has been shown to:

- Disorient migratory birds
- Disrupt flight trajectories
- Prolong migration duration
- Increase survival challenges (Engels et al., 2014)

Thus, EMR may impair long-distance migratory success and ecological connectivity.

➢ *Reproductive and Developmental Toxicity:*

Studies on avian species indicate that RF exposure can negatively affect reproductive functions through:

- Decreased sperm viability and motility
- Reduced egg fertilization and hatchability
- Impaired embryonic development
- Altered hormonal regulation (Cucurachi et al., 2013; Balmori, 2010)

For example, house sparrows and pigeons nesting near mobile towers showed reduced clutch sizes and increased nest abandonment, suggesting that chronic exposure may threaten population stability (Balmori & Hallberg, 2007).

➢ *Behavioral and Cognitive Disturbances:*

Behavioral responses are often early indicators of EMR-induced stress. Field observations report:

- Decreased nest density and altered roosting patterns
- Reduced vocalization and breeding communication
- Elevated anxiety and predator avoidance behavior (Everaert & Bauwens, 2007)

Such disturbances may impair feeding efficiency, reproductive success, and social bonding, ultimately contributing to local population decline.

➢ *Specific Absorption Rate (SAR) Sensitivity in Birds:*

Due to their small body size, thin tissues, and high surface-area-to-volume ratio, birds absorb more RF energy per unit mass than larger animals. Birds perching close to antennas (within near-field zones) experience significantly

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higher SAR values (Russell, 2018). This localized absorption may produce both thermal and long-term non-thermal effects.

Collectively, these mechanisms suggest that increasing EMR exposure poses emerging risks to avian biodiversity—particularly for urban and migratory species.

IV. FIELD AND EXPERIMENTAL EVIDENCE OF EMR IMPACTS ON BIRDS

Empirical evidence on electromagnetic radiation (EMR) effects in avian species combines field observations, controlled laboratory experiments, and modeling studies. These studies provide insight into both behavioral and physiological consequences, as well as dose–response relationships.

➢ *Field Observations:*

Urban and suburban environments, with dense telecommunication infrastructure, provide natural laboratories to study EMR exposure in birds. Key observations include:

- *Population Declines:*

House sparrows (*Passer domesticus*) and starlings (*Sturnus vulgaris*) show reduced abundance in proximity to mobile phone base stations, particularly in high-density urban areas (Balmori & Hallberg, 2007; Everaert & Bauwens, 2007).

- *Behavioral Alterations:*

European robins (*Erithacus rubecula*) exposed to ambient RF-EMF exhibit disorientation during migratory tests, suggesting interference with magnetic compass orientation (Engels et al., 2014; Wiltschko et al., 2015).

- *Reproductive Disruption:*

Nest abandonment, reduced clutch size, and delayed hatching have been recorded near high-intensity EMR zones, indicating chronic stress and potential population-level effects (Balmori, 2010; Cucurachi et al., 2013).

➢ *Laboratory and Controlled Experiments*

Laboratory studies allow precise control of EMR frequency, intensity, and exposure duration:

- *Sparrows and Pigeons:*

Chronic exposure to 900 MHz fields caused increased oxidative stress, decreased sperm quality, and lower hatchability rates (Cucurachi et al., 2013; Panagopoulos et al., 2015).

- *Magnetoreception Studies:*

Weak EMF interference (10–100 nT) disrupted orientation behavior in migratory birds, confirming a non-thermal mechanism affecting cryptochrome-based navigation (Ritz et al., 2004).

- *Dose–Response Effects:*

Exposure intensity and duration correlate with biological impact; higher field strengths and prolonged exposure increase oxidative stress, reproductive impairments, and behavioral anomalies (Hardell & Carlberg, 2020).

➢ *Exposure–Response Patterns Across Species*

Small Passerines (e.g., sparrows, robins) are highly sensitive due to high surface-area-to-volume ratios, resulting in elevated Specific Absorption Rate (SAR) values.

Columbidae (pigeons, doves) show reproductive and developmental delays under chronic RF exposure.

Migratory Species experience navigation disruption even at low-intensity EMFs, highlighting species-specific vulnerability (Engels et al., 2014).

➢ *Geographic and Habitat Considerations*

- *Urban Areas:*

Higher infrastructure density → stronger cumulative EMR exposure → elevated risk of reproductive and behavioral impacts.

- *Rural Areas:*

Sparse towers → lower exposure; however, migratory birds may still encounter high-intensity zones during stopovers.

- *Global Patterns:*

Studies from Europe, Asia, and North America consistently indicate EMR-related behavioral and reproductive effects, though methodology heterogeneity limits direct comparison (Balmori, 2009; Russell, 2018).

➢ *Knowledge Gaps:*

Despite growing evidence, critical gaps remain:

- Limited longitudinal population studies quantifying cumulative EMR effects.
- Sparse data on millimeter-wave 5G exposure in free-living birds.
- Need for standardized SAR measurements across species and habitats.
- Interaction with other environmental stressors (pollution, climate change) remains poorly understood.

V. MITIGATION STRATEGIES AND POLICY RECOMMENDATIONS:

The increasing prevalence of anthropogenic electromagnetic radiation (EMR) necessitates the development of mitigation strategies to minimize its impact on avian populations. Given the demonstrated behavioral, reproductive, and physiological hazards of EMR, a combination of technical, ecological, and regulatory measures is essential.

➢ *Exposure Limit Guidelines:*

Regulatory bodies such as the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the World Health Organization (WHO) provide human safety limits for RF exposure. However, these standards do

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not explicitly address wildlife or avian species (Russell, 2018). It is recommended to adopt conservative exposure limits for sensitive habitats, including nesting sites and migratory corridors.

SAR thresholds for small birds should be established based on species-specific absorption modeling and laboratory data (Cucurachi et al., 2013).

➢ *Antenna Placement and Tower Siting:*

Urban planning and telecommunication policies should incorporate avian risk assessments in tower siting:

- Avoid placing high-power antennas near known bird roosting and nesting sites, wetlands, and migration stopovers.
- Promote height and orientation adjustments to reduce radiation hotspots in areas frequented by birds.
- Implement buffer zones around critical habitats to minimize chronic exposure (Balmori, 2010).

➢ *Technological Mitigation Measures:*

- *Beamforming and Power Management:*

Reducing transmitted power in directions of bird habitats during peak nesting periods.

- *Shielding and Enclosure Design:*

Antenna towers and devices can be modified to minimize EMR leakage at ground level.

- *Monitoring and Early-Warning Systems:*

Broadband survey meters and frequency-selective meters can track real-time EMR intensity in sensitive areas (Kumar et al., 2023).

➢ *Habitat and Biodiversity Conservation Strategies:*

- *Urban Green Infrastructure:*

Maintaining large, EMR-shielded green spaces supports safe nesting and foraging.

- *Migration Corridor Protection:*

Mapping and protection of key stopover sites from dense EMR exposure.

- *Species-Specific Conservation Plans:*

Focused monitoring for vulnerable species such as migratory passerines and raptors.

➢ *Research and Policy Recommendations:*

- *Standardized Long-Term Studies:*

Integrate field and laboratory data to establish robust dose–response relationships.

- *GIS-based Risk Mapping:*

Use spatial modeling to identify EMR hotspots relative to avian habitats.

- *Policy Integration:*

National telecommunication authorities should consider avian health in EMR regulations, including 5G deployment guidelines.

- *Public Awareness:*

Promote knowledge among urban planners, environmental agencies, and the general public regarding EMR impacts on birds.

VI. CONCLUSION

Birds are increasingly exposed to anthropogenic electromagnetic radiation (EMR) due to the global expansion of wireless communication infrastructure, including mobile towers, Wi-Fi networks, and emerging 5G technology. The evidence compiled in this review demonstrates that EMR can adversely affect avian species through multiple mechanisms, including oxidative stress, magnetoreception disruption, reproductive toxicity, and behavioral alterations. Small body size, high metabolic rates, and reliance on geomagnetic cues render birds particularly vulnerable to both thermal and non-thermal effects of EMR (Cucurachi et al., 2013; Engels et al., 2014; Ritz et al., 2004).Field and laboratory studies consistently show that chronic EMR exposure can lead to disorientation in migratory birds, reduced reproductive success, altered nesting behavior, and population declines, especially in urban and peri-urban environments (Balmori & Hallberg, 2007; Everaert & Bauwens, 2007). The introduction of high-frequency 5G networks has amplified potential risks due to denser transmitter deployment and millimeter-wave radiation, emphasizing the need for precise exposure assessment, including specific absorption rate (SAR) modeling and GIS-based spatial mapping (Russell, 2018; Kumar et al., 2023).

Despite this growing evidence, significant knowledge gaps remain. Long-term, longitudinal studies on free-living avian populations are limited, and data on cumulative, multi-frequency exposures are scarce. Moreover, species-specific SAR thresholds and interactions with other environmental stressors such as pollution and habitat fragmentation remain poorly understood. To mitigate potential risks, a combination of technical, ecological, and regulatory strategies is recommended. These include careful tower siting, urban planning that considers avian habitats, real-time EMR monitoring, species-specific risk assessments, and adoption of conservative exposure limits in ecologically sensitive areas. Research priorities should focus on multi-disciplinary approaches combining field observations, laboratory experiments, and spatial modeling to establish robust dose–response relationships and develop evidence-based conservation policies.

In conclusion, protecting avian biodiversity in the era of expanding wireless networks requires integrated scientific assessment, targeted policy measures, and public awareness initiatives. By proactively addressing EMR exposure risks, it is possible to balance technological progress with the conservation of bird populations and ecosystem integrity.

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