Kashmir Journal of Science

https://kjs.org.pk **ISSN: 2958-7832**

Kashmir Journal of Science (2025), 4(4):24-34; DOI: https://doi.org/10.63147/krjs.v4i4.225

Review Paper

Effects of Ionizing and Non-Ionizing Radiation on Animal Physiology and Behaviour: An Interdisciplinary Review

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ARTICLE INFO

Article history:

Received: 16-11-2025

Revised: 12-12-2025

Accepted: 24-12-2025

Available online: 31-12-2025

Keywords:
Radiation Exposure, Oxidative Stress, Animal Physiology, Behaviour, Vertebrates, Invertebrates

Abstract

The radiation affects animals differently based on their kind, intensity and animal biology. Direct impairment of DNA and weakening of the immune system and an augmentation of oxidative stress may be produced by ionizing radiation like X-rays and gamma rays. Non-ionizing radiation (ultraviolet light, electromagnetic fields) does not fragment the bonds between atoms, but can alter hormonal balance, reproduction, behaviour and circadian rhythms. Studies conducted in the highly polluted areas such as Chernobyl and Fukushima, and also in controlled laboratory research indicate that the animals are not responsive to radiation. This is more sensitive to amphibians and some bird species and the inefficiency of the DNA repair system and the resilience of antioxidant systems helps some insects and invertebrates to cope with it. Such effects on the environment usually go outside individuals and interfere with population structure, migration, reproduction and food-web stability. The review unites both vertebrates and invertebrates' evidence to compare the effects of radiation on their physiology and ecology. It marks significant processes like oxidative stress, DNA damage, hormonal destabilization and behavioural alteration. These responses have important implications on understanding the protection of wildlife and also on the establishment of realistic radiological safety standards and future research priorities.

Introduction

Radiation exists naturally in our environment and different types of radiation influence animals in different ways. Some forms are harmless or even useful, while others have the potential to damage living tissues. Scientists classify radiation into two main types. Ionizing radiation includes X-rays and gamma rays. It carries enough energy to remove electrons from atoms and can directly damage DNA. Non-ionizing radiation includes ultraviolet light, microwaves and radiofrequency waves. It does not break atomic bonds, but it can interfere with hormones, behaviour and normal cellular activity (Hall & Giaccia, 2023).

Radiation exposure has always existed in the natural environment, but modern human activity has significantly altered both its intensity and form. Medical imaging, satellite communication and especially nuclear accidents such as Chernobyl and Fukushima have contributed to higher levels of radiation in the air, soil and water. According to international reports, the Chernobyl disaster caused long-term radioactive contamination of ecosystems and wildlife habitats (IAEA, 2020). Field-based studies also show that chronic exposure to ionizing radiation in such regions can increase mutation rates and genetic instability in animals (Møller & Mousseau, 2015). The biological effect of radiation, therefore, depends not only on the dose and duration of exposure but also on the type of radiation and the sensitivity of the species involved.

Among vertebrates, amphibians and reptiles are especially vulnerable. Their thin skin, external egg development and slower metabolism make them more sensitive to both ionizing radiation and ultraviolet radiation. They often show DNA damage, immune stress, hormonal imbalance and reduced fertility. Large-scale studies also confirm that UV-B radiation negatively affects freshwater and marine organisms (Bancroft et al., 2007).

In contrast, some insects and birds show a higher level of resistance because of faster reproduction and better antioxidant defense systems. These variations show that radiation does not affect all organisms equally. Figure 1 presents a simple overview of how ionizing and non-ionizing radiation influence animal physiology and behaviour. It introduces the basic concepts that are discussed in detail in the following sections.

Radiation affects animals in different ways at the cellular and physiological levels, but understanding these effects in real-world environments is equally important. To explore how wildlife responds outside controlled laboratory settings, scientists have studied regions where radiation has remained in the environment for years. Over the past few decades, areas such as Chernobyl and Fukushima have served as natural laboratories, allowing researchers to observe the long-term and chronic effects of radiation on different animal groups (Garnier-Laplace et al., 2013; IAEA, 2020). These studies reveal that no single pattern of response exists. The impact of radiation changes with species type, life stage, metabolic rate and surrounding environmental conditions.

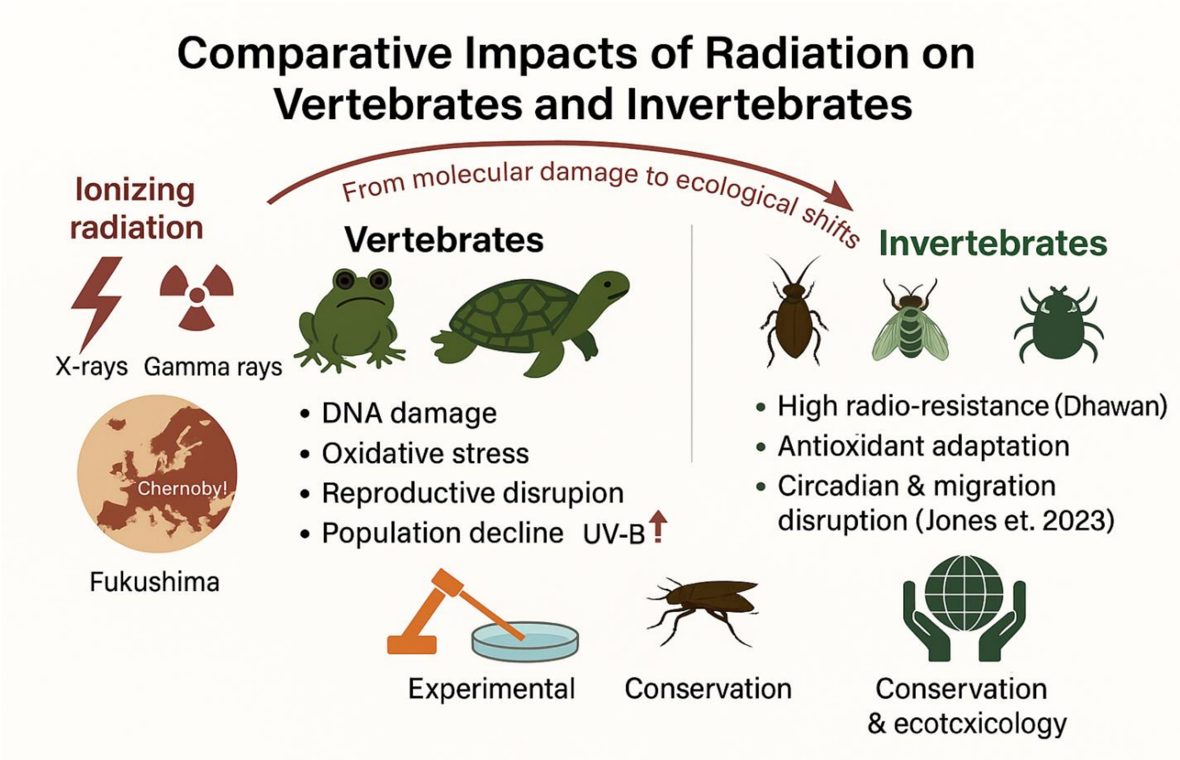

Figure 1: A simplified illustration of how different types of radiation influence animals. Ionizing radiation mainly causes DNA damage and triggers oxidative stress inside cells. Non-ionizing radiation does not break DNA directly but can disturb hormones, sensory functions and normal movement behaviour.

Among vertebrates, amphibians and reptiles receive special attention because of their permeable skin, temperature-dependent metabolism and life cycles that include both aquatic and terrestrial phases. Certain groups of amphibians in the Chernobyl Exclusion Zone have indicated tolerative behavior, including normal telomere length and consistent stress hormone levels (Burraco et al., 2021). Conversely, other researches have indicated a decrease in survival of the amphibians during the interaction of UV-B radiation with other factors such as low pH or disease (Blaustein et al., 2008). Oxidative stress and reduced reproductive success, impaired immune system and altered behaviour are also associated with birds and mammals that are affected by radiation in their area (Galván et al., 2014). Non-ionizing radiation has also been found to have quantifiable sensitivity in freshwater organisms. Exposure to UV-B light, as an example, has been proven to cause death and antioxidant stress reactions in *Daphnia magna*, which is an important planktonic species in aquatic food webs (Borgeraas & Hessen, 2000).

The invertebrates tend to respond the radiations differently. The insects and arthropods have robust antioxidative systems and DNA-repair systems, which enable them to endure radiation intensities that may be fatal to vertebrates (Ikeda et al., 2019). Non-ionizing radiations like electromagnetic fields and UV radiation are however more sensitive to them in their early developmental stages. These exposures may cause interruption in behaviour, sensory perception and reproduction.

Radiation does not have an effect on individual organisms alone. It is able to transform populations, disrupt predator-prey interactions, lower fertility, alter sex ratios and disrupt migration behaviour. All these ecological impacts point to the necessity to research radiation impact in a wider environmental framework rather than the narrower lens of medical or genetic consequences. The ecological data, radiobiology, toxicology and environmental physics approach should combine to provide proper risk assessment, policy making for wildlife protection.

Methodology

This study is based on a qualitative literature review. Research articles were collected from PubMed, Scopus and Google Scholar using keywords such as "radiation exposure," "vertebrate response," "UV-B effects," "oxidative stress," and "Chernobyl animals." Only peer-reviewed studies on animals (vertebrates or invertebrates) exposed to ionizing or non-ionizing radiation were included. Human-only studies, non-scientific reports or papers without biological relevance were excluded.

Instead of a statistical meta-analysis, a narrative synthesis was used to compare results across species, radiation types and ecological settings. Findings were organized into major themes:

- Effects of ionizing radiation on vertebrates
- Effects of non-ionizing radiation (UV, EMF)
- Responses of invertebrates
- Cross-taxa comparisons and ecological implications

This approach allows integration of physiological, behavioural and ecological evidence from both field and laboratory studies.

Discussion

Radiation Effects on Vertebrates

Radiobiology of vertebrates and particularly, of amphibians, reptiles, birds and mammals are popular research models for studying the effects of radiation on higher organisms. Due to their longer life span, developed organ systems and ecological importance, they are good biological indicators of radiation stress.

Ionizing radiation

Ionizing radiation (gamma rays, X-rays, beta particles) has enough energy to break chemical bonds and damage DNA. In many vertebrates, it leads to oxidative stress, cell death, immune suppression and reduced fertility. Amphibians, especially frogs living in the Chernobyl Exclusion Zone, have been studied extensively. Some species like *Hyla orientalis* showed almost normal stress hormone levels and telomere length, suggesting possible adaptation over time (Burraco et al., 2021). However, in many other vertebrates, long-term exposure results in chromosomal damage, higher mutation rates and developmental abnormalities (Galván et al., 2014).

Non-ionizing radiation (UV and EMF)

Non-ionizing radiation such as ultraviolet (UV-B) light and electromagnetic fields (EMF) does not directly break DNA, but it can still disrupt biological systems. UV-B exposure reduces survival in amphibian eggs and tadpoles, especially when combined with low pH or infections (Blaustein et al., 2008). Birds and mammals exposed to artificial EMF may experience altered melatonin levels, disrupted sleep cycles and disoriented migration behaviour.

Sensitivity differences among vertebrates

Not all vertebrates respond the radiations in the same way. Amphibians and reptiles are more sensitive because of their permeable skin and low metabolic rates. Birds and mammals have better DNA repair and antioxidant systems but still show reduced fertility, weakened immunity and neurological problems under long-term exposure (Hinton et al., 2007). Environmental factors such as temperature, habitat, diet and life-stage also influence the level of damage.

Radiation affects multiple biological systems in vertebrates, including DNA, immune function, reproduction, neural activity and hormonal regulation. These variations depend on the radiation type, dose and species involved. In particular, non-ionizing radiation such as near-ultraviolet light has been shown to suppress melatonin production in the eyes of birds, indicating direct disruption of hormonal and circadian pathways (Zawilska & Rosiak, 2000). Table 1 summarizes the major systems affected by ionizing and non-ionizing radiation in animals.

Table 1: Summary of Radiation Effects on Vertebrate Biological Systems

Radiation Type	Biological System Affected	Observed Effect	Representative Species	Key References
Ionizing (e.g., X-rays, gamma)	DNA, Immune System	DNA strand breaks, oxidative stress, immunosuppression	*Rattus norvegicus*, *Danio rerio*	Møller & Mousseau (2015)
Ionizing	Nervous System	Cognitive impairment, anxiety behaviour	*Mus musculus*	Kolesnikova et al. (2023)
Non-ionizing (RF-EMF, UV-A)	Reproductive System	Reduced sperm motility, oxidative stress, and DNA damage	*Xenopus laevis*, birds	De Iuliis et al. (2009)
Non-ionizing	Endocrine, Brain / Reproductive	Altered melatonin, disrupted sleep cycles, behavioural and reproductive stress	*Gallus gallus, Mus musculus*	Dyche et al. (2006); Aburawi et al. (2020)

Radiation Effects on Invertebrates

More than 99 percent of the animals in the animal kingdom have no backbone, and they include insects, crustaceans and mollusks. Due to their short lifecycles, high fecundity and ecological significance, they are good indicators in radiation impact studies. Contrary to vertebrates, the majority of invertebrate species are surprisingly resistant to radiation, particularly ionizing radiation.

Ionizing radiation and tolerance

Several insects, such as fruit flies (*Drosophila melanogaster*), demonstrate strong resistance to ionizing radiation. They possess efficient DNA repair systems and natural antioxidant defenses that help them survive radiation doses that would be lethal to most vertebrates (Ikeda et al., 2019). However, sensitivity increases during early developmental stages, such as larvae or pupae. In aquatic invertebrates like *Daphnia magna*, gamma radiation can still produce oxidative stress, growth delays and reduced reproduction when exposure levels are high (Gomes et al., 2018).

Non-ionizing radiation (UV and electromagnetic fields)

Non-ionizing radiation affects invertebrates differently. UV-B radiation can damage larvae, delay molting and reduce egg survival in insects and crustaceans. Some species, like *Artemia* and *Daphnia*, produce protective pigments and antioxidants that limit UV damage, but many others lack such protection.

Electromagnetic fields (RF/EMF) from mobile towers and communication devices can interfere with insect behaviour, navigation and reproduction. Studies report changes in honeybee orientation, altered circadian activity and reduced brood development under prolonged EMF exposure (Cucurachi et al., 2013; Levitt et al., 2022).

Ecological importance

Because invertebrates are essential for pollination, decomposition and food chains, any decline in their populations affects entire ecosystems. Reduced insect populations can disrupt bird feeding, plant reproduction and soil health. Due to their high sensitivity to environmental change, some invertebrates are now considered effective bioindicators in radiation-affected regions such as Chernobyl and Fukushima.

Cross-taxa comparative analysis and ecological implications

Radiation has an impact on vertebrates and invertebrates, but the sensitivity to radiation, means of surviving under radiation exposure and ecological effects are different. By comparing these responses, scientists can better understand why some species are more susceptible than others and how radiation can reshape whole ecosystems. Radiation does not influence all biological systems equally. Ionizing radiation primarily affects DNA, immune and nervous systems, whereas non-ionizing radiation more commonly disrupts reproductive, endocrine and neural functions. This distribution of system-specific effects is illustrated in Figure 2.

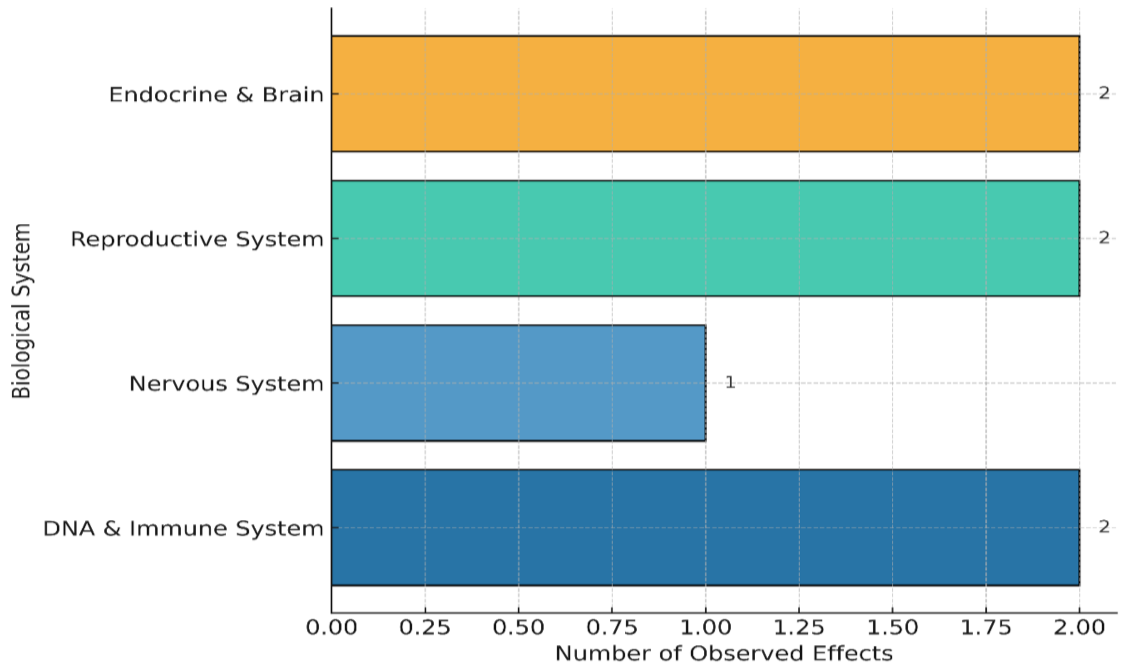

Figure 2: Overview of the biological systems most commonly affected by different types of radiation. Ionizing radiation tends to damage DNA, suppress immune function and trigger oxidative stress, whereas non-ionizing radiation more often interferes with hormonal activity, reproduction and neural responses.

Sensitivity: Vertebrates vs. Invertebrates

Vertebrates, especially amphibians and reptiles, are more prone to radiation damage. Their permeable skin, slower metabolism and external egg development make them highly sensitive to both ionizing and UV-B radiation. They often show DNA damage, hormonal imbalance, immune stress and reduced fertility, and extensive meta-analyses also confirm that UV-B radiation significantly affects freshwater and marine vertebrates in similar ways (Bancroft et al., 2007).

Birds and mammals have stronger antioxidant and DNA repair systems. However, long-term radiation exposure still leads to neurological issues, lower reproduction rates and behavioural changes, especially in contaminated regions like Chernobyl and Fukushima.

Invertebrates, particularly insects, generally show greater resistance to ionizing radiation because of their short life cycles, rapid reproduction and efficient DNA repair systems. However, they are more susceptible to non-ionizing radiation such as intense UV light or electromagnetic fields, especially during egg or larval development. The post-Fukushima field studies indicate that even insects that are radiation tolerant may experience biological damage; such as the pale grass blue butterfly exhibited wing abnormality, decrease in life and inheritance of genetic mutations over successive generations (Hiyama et al., 2012).

Common Biological Mechanisms

Despite their differences, both groups share some similar biological responses:

- Oxidative stress caused by radiation-induced free radicals
- Activation of antioxidant enzymes like catalase (CAT) and superoxide dismutase (SOD)
- DNA ends and genomic modifications of both vertebrate and invertebrate cells.
- Hormonal and behavioural alterations such as disturbed sleeping patterns, navigation problems and disturbed responses to stress.

What is common in these mechanisms is the fact that radiation is able to perform its functions at a molecular level before it influences tissues, organs, and, finally, populations.

Ecological and Population-Level Effects

Radiation does not only affect individual organisms but can also reshape ecosystems by:

- Reduced breeding success and delayed development affect population size (Cannon & Kiang, 2020).
- Predator–prey relationships change when sensitive species decline (Mappes et al., 2019; Bonacic et al., 2023).
- Pollination decreases if insect communities are disturbed (Møller et al., 2012; Lázaro et al., 2016; Balmori, 2021).
- Migration routes of birds, fish and insects are disrupted when navigation is impaired (Lerebours et al., 2018).
- Over time, these changes may weaken food webs and lead to biodiversity loss (Mappes et al., 2019; Bonacic et al., 2023).

Tolerant species like some insects or radiation-adapted amphibians are also able to survive to reproduce (Balmori, 2021). But when major species such as the pollinators, amphibians or small mammals are reduced, the whole ecosystem gets to be unstable (Bonacic et al., 2023).

Conclusion and Future Directions

Radiation impacts living organisms on many levels, from DNA structure to the ability of a species to survive. This review demonstrated that ionizing radiation, in the form of X-rays and gamma rays, causes molecular damage, genetic mutations, oxidative stress, and immune suppression in a wide range of vertebrates; amphibians seem particularly susceptible, followed by birds and mammals. By contrast, non-ionizing radiation, in the form of UV light and electromagnetic fields, does not directly break DNA yet still interferes with hormonal balance, reproductive function, and behavior.

Generally, invertebrates are more resistant to radiation than vertebrates, though their juveniles and reproductive systems retain sensitivity to high UV exposure or radiofrequency fields. The species-specific effects in both vertebrates and invertebrates include common biological responses that involve oxidative stress, the activation of DNA repair mechanisms, and alterations in endocrine signals.

Radiation exposure also shapes ecological systems. Reduced reproduction, disrupted migrations, altered predator-prey relationships, and pollination decline have been reported in regions such as Chernobyl and Fukushima. These findings emphasize the fact that radiation is not only a medical concern but also an ecological and conservation issue.

Future Research Recommendations

To improve understanding and protection of wildlife, future studies should focus on:

- Long-term ecological monitoring of radiation-exposed regions to track population recovery or decline.
- Comparative genomics and proteomics to identify genes responsible for radiation resistance or sensitivity in different species.
- Combined stress studies, where radiation is studied together with climate change, pollution, disease or habitat loss.
- Non-ionizing radiation research, especially on electromagnetic fields and how they affect pollinators, navigation and animal reproduction.
- Policy-oriented studies, linking radiation biology with environmental law, wildlife protection and safe radiation management.

Conflict of Interest

The authors declare no financial or personal conflicts of interest that could have influenced the outcomes of this study.

Funding
This research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors.

Use of Artificial Intelligence (AI) Tools – Ethical Statement

Artificial intelligence tools were used only for language refinement, grammar correction and improving readability. The scientific content, interpretation of data and final conclusions were entirely developed and verified by the authors.

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