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Systems Biology Approach to Deciphering the Multilevel Impact of Pollution on Animal Physiology / Review Article

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Abstract. Pollution has strongly increased during the past decades due to intensive industrial activities, expansion of agriculture and urban areas, as well as increasing use of chemicals, heavy metals, POPs, and other novel industrial pollutants like micro plastics, these can affect health in animals and ecosystems on levels ranging from molecular changes in genes and proteins up to disturbances in metabolism and organ functions, including behavioral and social changes, which again may impede survival, reproduction, and biodiversity.

Traditional single measure approaches cannot conceptualize the complexity and time-course variability of the biological response to pollution. Systems biology allows a holistic perspective on such effects by way of integrated molecular, proteomic, metabolic, tissue-level, and behavioral data. It will be able to deliver early biomarkers, identify adaptive and compensatory mechanisms used by organisms under stress, and give more reliable estimates of risks for the environment. Systems biology will continue to enable effective strategies in environmental protection, including those relevant to environmental pollutants, sentinel species as bioindicators, and predictive modeling of new or chronic pollutants. This approach faces several significant challenges, including the complex nature of both the data and biodiversity, the limited availability of high-resolution environmental data, the requirements for advanced computational tools, and the need for integrated, multi-level models. The study concluded that animal health and ecosystem stability are compromised at all levels of environmental pollution.

Keywords: Environmental pollution, animal health, systems biology, biomarkers, biodiversity

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1. Introduction: With intensive industrial activities, agricultural expansion, rapid urbanization, and wide use of chemicals from all sectors, including pesticides, fertilizers, and organic and inorganic industrial pollutants during the last few decades, levels of environmental pollution have worsened (Scheringer *et al.,* 2020; Doughton, 2018). This has translated eventually into large-scale changes both at aquatic and terrestrial ecosystems levels, with organisms, like animals, being exposed to an increased variety of pollutants, these include toxic metals such as mercury, lead, and cadmium, long-lasting organic pollutants, and a variety of industrial chemicals like modern pesticides and micro plastic residues (Lee *et al.,* 2022). It has only been realized recently that these pollutants cause multi-level disturbances in animals-from molecular and genetic changes, through behavioral, functional, and systemic changes-which affect the ability of individuals to survive and reproduce, and hence their health and biodiversity. Such disruption may include endocrine disorders, oxidative stress caused by an increase in ROS, immunosuppressant, developmental abnormalities, and reproductive damage. Traditional approaches toward the understanding of the impact of the environment have often focused on single level indicators, such as pollutant concentration in blood or the activity of some liver enzymes. Biological systems represent, in fact, complex dynamic interrelationships among molecules, cells, tissues, and organs in a network of interactions (Hod & Friend, 2011). From this perspective, systems biology is an approach which has started to enrich the understanding of the multi-level impacts of pollution by integrating data from the molecular, protein, metabolic, and tissue levels into portraying organism responses as integrated systems (Keitano, 2002). Thus, systems biology enables the identification of compensatory and adaptive mechanisms employed by organisms under environmental stresses, such as modulation of gene expression for detoxification, increasing antioxidant activity, or changing feeding and reproductive behavior. In this respect, the latter approach may be used in the future in long-term assessments with the aim of predicting the effects of a given pollutant on environmental health and on the health of organisms, providing further guidelines on how to design effective strategies of environmental remediation.

2. Pollution and its multi-layered impacts

2.1 Molecular Effects: These subtle but significant changes in animal cells most likely modulate gene expression, protein modification, or the activation of cellular signaling pathways related to oxidative stress and detoxification responses. Such will form the molecular mechanisms of pollens action.

For instance, in fish exposed to such POPs as PCBs, increased activities of detoxification enzymes such as CYP1A can be detected and may indicate cellular adaptation to chemical stress. Lead and cadmium, on the other hand, may induce DNA damage, mutation rates, and interfere with DNA repair processes, which might possibly affect survival and reproductive productivity.

Other studies indicate that toxic pollutants induce genetic changes in the population of animals and, thus, increase the impacts on the progeny of such animals (Galloway *et al.,* 2004).

2.2 Metabolic Effects: The other major metabolic pathways that are targeted equally by the pollens are mitochondrial energy production and metabolism of proteins, lipids, and carbohydrates. The heavy metals reduce the efficiency of the mitochondrial respiratory chain; this increases ROS and oxidative stress leading to protein, lipid, and nucleic acid damage (Stohs & Bagchi, 1995; Valko *et al.*, 2005).

Recent studies have also established that exposure to POPs disrupts metabolic and hormonal balances, inducing insulin resistance and fatty liver diseases. Thus, it is valid to say that environmental pollution can be linked to metabolic disorders in animals and humans (Xu *et al.,* 2020).

2.3 Organ-Level Effects: All these molecular and metabolic changes cumulatively affect the functional activity of organs such as the liver, kidneys, heart, thyroid gland, and immune system. Birds, when exposed to heavy metals including lead, produce fewer antibodies and thus are highly prone to infectious and chronic diseases (Burger 2008; Eva *et al.* 2010).

It also includes disturbance in the liver detoxification function, accumulation of pollutants in tissues, disruption of hormonal balances, disturbance of cortisol and adrenaline levels, suppression of immune responses against chronic pollution.

2.4 Behavioral Effects: Anthropogenic environmental pollutants have great influence on animal behavior like feeding, locomotors activities, and reproductive behavior. Organic pollutants have been reported to decrease the activity of fishes and birds and have shown less mating behavior. (Weiss and Weiss, 2004; Ankle *et al.,* 2009), these changes in behavior directly influence their survival and reproductive success, hence amplifying the ecological imbalances among animal populations. Recent studies by Grandjean and Landrigan, 2014 show that chronic exposure leads to long-lasting changes in the social behavior and neurological functions of small mammals besides problems in learning and memory.

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3. Systems Biology: A Tool for Assessment

3.1 Definition of Systems Biology: Systems biology is the newest scientific approach whereby organisms are understood as integrated dynamic systems, not as independent components. According to Abdullah, Mohammed, R.A., *et al.* (2024), and Afdal, *et al.* (2024), this approach brings together knowledge from many different levels including:

Genomics: It deals with genes and the changes in their expression due to pollutants ◦incluude Proteomics, this involves the analysis of proteins, including post-translational modifications related to detoxification and responses to oxidative stress and Metabolism, this studies the metabolic pathways of energy, lipids, proteins, and carbohydrates, looking for any changes.

Ecophysiological and Behavioral Data: The process of monitoring the behavioral and physiological responses in organisms relative to environmental stressors.

Systems biology investigates the influence of environmental factors, including contaminants, using dynamic network analysis and mathematical modeling on cellular processes, tissues, and the whole organism.

The paper overviews some mechanisms of an organism in adapting or compensating for environmental stressors by focusing on the up regulation of antioxidant enzymes, alterations in mitochondrial energy production, and changes in feeding and reproductive behaviors.

3.2 Applications in Pollution Studies: The systems biology concept is very useful in the understanding of animals' responses to environmental pollutants and ecosystems. These applications include:

1. Forecasting Environmental Hazards: By modeling interactions of biological networks, science can predict how animals will respond to new or synthesized pollutants well in advance of obvious environmental damage occurring (Hod and Friend, 2011) include predict the chronic effects of lead or cadmium on cellular energy production and oxidative stress in fish and identifying the vulnerabilities at a molecular and organelle level may enable early interventions.

2. Identification of Specific Biomarkers: It allows systems biology to identify molecular, proteomic, and metabolic biomarkers of such damage at an early stage.

Gene expression of detoxification enzymes includes CYP1A and GSTs. ROS and other markers of oxidative stress. Immune response and proteins associated with inflammation. This is attributed to the hormonal changes associated with growth and reproductive life, as shown by Schlezinger *et al.,* 2019; BaiL *et al.* 2024; DagdagO 2023, These biomarkers offer monitoring that is more sensitive and wider in scope than that previously afforded by traditional approaches focused on single parameters.

3. Environmental protection and intervention design Network analysis: The explanation of pollutants with metabolic and organic pathways, thus helping in the development of remediation techniques for the soil and water that have been contaminated. Guardian species act as bioindicators to guide ecosystem restoration and environmental policy to reduce toxic emissions, focusing on the protection of biodiversity.

4. Multi-level impact assessment: Systems biology depends on data gathered from the molecular to the behavioral levels of the organism and takes into consideration the full breadth of the effects of pollutants on organisms, including gene expression and cellular signaling effects; metabolic changes in energy production and nutrient utilization; organs that may become dysfunctional include the liver, kidneys, thyroid gland, and immune system; and behavioral changes impacting feeding, locomotion, and reproduction.

5. Analysis of adaptive and compensatory responses: This may reveal some mechanisms of resistance that naturally develop in animals, including the following: increased production of antioxidants that can neutralize oxidative stress; modification of energy metabolism in order to meet physiological demands under conditions given by pollutant exposure; and behavioral changes that enhance the chances of survival under conditions of a stressful environment. Such knowledge will enable the assessment of the resilience of organisms in polluted environments and give relevant recommendations for species conservation programs.

6. Prediction of long-term environmental and health impacts: Multilevel data integration, as described by KadimMK *et al.* (2022) and MoulinecA *et al.* (2025), allows researchers to predict such long-term impacts as biodiversity loss due to effects on survival and reproduction, changes in natural food webs and energy flows, and effects of bioaccumulation and biomagnification across tropical levels on higher-level species.

7. Challenges and Future Prospects of Systems Biology in Pollution Assessment Despite: The significant developments which have so far been realized in systems biology in respect to environmental pollution, there are still a number of grand challenges that remain:

1. Data complexity and integration: Systems biology brings together multi-omics datasets, from genomic, proteomic, and metabolic even to environmental and behavioral data. Such coordination and integration are highly difficult because of the diversity, quality, temporal accuracy, and spatial resolution of these measurements. Further complications arise when formulating appropriate predictive models due to complex interrelationships between the environment and biological systems.

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2. Biodiversity and Species Variation: Biological systems, however, exhibit a high degree of variability between species and sometimes within the same species. Thus, generalization on all animals or across all ecosystems is impossible. The model should, therefore, be flexible enough to take into consideration the genetic variability, physiological diversity, and functional diversity between organisms. (Hod and Friend, 2011).

3. Limitations of High-Resolution Environmental :Data Most of the environmental studies are missing detailed information on the actual concentrations of all the pollutants, their chemical forms, and the duration of exposure in natural ecosystems. Without this, predictive models will not perform well and in this case, according to Scheringer *et al.* (2020), long-term consequences for wildlife or ecosystems are practically impossible to predict.

4. The need for high-level Computing tools. To handle and analyze large-scale systems biology data, high-performance computing and advanced algorithms for network modeling, data integration, and prediction of complex pollutant interactions with biological pathways become necessary. These are the tools that will be required to increase predictive accuracy and reliability in environmental risk assessment.

5. Integration Across Multiple Environmental Contexts: With Tahir, Alkheraije, 2023, and Zahran, *et al.,* 2025, in the future, multi-level and multi-environmental data across terrestrial and aquatic ecosystems will be combined, considering various types of pollution, multiple climatic conditions, and biodiversity patterns. This would be in line with integrated knowledge at the molecular, physiological, behavioral, and environmental levels of data, thus enabling one to comprehend the effect of pollutants on every biological level. Outlook: However, despite these challenges, it is clear that the prospects for systems biology in pollution assessment are good.

Developing the broad-based databases of pollutant impacts that document the genetic, metabolic, and behavioral responses of various species; applying artificial intelligence and machine learning to complex datasets to predict, at various levels, the impacts of pollutants; attempting to integrate systems modeling with real-world environmental monitoring through the application of both remote sensing and field environmental monitoring to predict the impacts of next-generation pollutants before harm occurs, enabling the establishment of preventative strategies and the management of ecosystems.

5. Conclusion:

This represents a multilevel threat to animal health and ecosystems, from subtle molecular modifications to metabolic, organic, and behavioral dysfunctions. These effects impinge directly on organism survival and reproduction, culminating in ecosystem disruption and loss of biodiversity. There is thus a dire need for effective management and mitigation. An integrative approach to systems biology, in this context, therefore, becomes an effective tool for a comprehensive understanding of these effects. Systems biology allows a more precise assessment of the impact of the environment based on interactions at the molecular, proteomic, and metabolic levels, but also physiological and behavioral ones. It allows early detection of biomarkers that indicate pollutant-induced stress before irreversible damage has occurred. Moreover, deeper insight is given into the way organisms maintain their adaptive and compensatory mechanisms against environmental stress, which could be through antioxidant activity, changes in gene expression, or by altered feeding/reproductive behavior. The application of systems biology, therefore, will become crucial and highly effective in the future for the protection of biodiversity. It shall ascertain changes at the molecular, physiological, and behavioral level in organisms and their capacity to adapt to pollution and efficient environmental interventions, ranging from strategies for soil and water remediation to the use of guardian species as bioindicators that monitor ecosystem health and predict long-term risk. The aim is to manage ecosystems so that impacts on food webs and energy flow are minimal in order to maintain healthy and sustainable wildlife populations in perpetuity. Comprehensive environmental risk assessment provides the overall holistic picture of the complex impacts on animals and ecosystems by integrating datasets at all levels. Systems biology is thus the scientific link between basic research and practical environmental management. It offers advanced frameworks for comprehensive understanding of the effects of pollution on wildlife and ecosystems and will be indispensable, therefore, in any future research with relevance to environmental protection, biodiversity conservation, and sustainable management of environments.

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