



INSECTS AS BIOINDICATORS: TINY SENTINELS IN MONITORING HEAVY METAL POLLUTION

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Abstract

Heavy metal pollution has emerged as one of the most persistent environmental challenges affecting terrestrial and aquatic ecosystems worldwide. Rapid industrialization, mining activities, urban expansion, intensive agriculture, and improper waste disposal have significantly increased the accumulation of toxic metals such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), and nickel (Ni) in the environment. Unlike organic pollutants, heavy metals are non-biodegradable and remain in ecosystems for long periods, where they accumulate in soil, water, sediments, plants, and living organisms. Conventional monitoring methods primarily rely on physicochemical analysis, which often fails to reflect the biologically available fraction of metals and their ecological impacts. In this context, insects are increasingly recognized as valuable bioindicators of environmental pollution because of their ecological diversity, rapid response to environmental disturbances, high sensitivity, and ability to bioaccumulate contaminants. Various insect groups including dragonflies, damselflies, beetles, ants, butterflies, chironomids, grasshoppers, and honey bees have been successfully used to assess heavy metal

contamination in terrestrial and aquatic ecosystems. Insect-based biomonitoring not only provides information about pollution levels but also helps in understanding ecological risks and trophic transfer of toxic metals. Recent advances in molecular biology, ecological toxicology, GIS, remote sensing, and analytical technologies have further strengthened the role of insects in environmental monitoring programmes. This article highlights the importance of insects as bioindicators, mechanisms of metal accumulation, major insect groups used in biomonitoring, and emerging approaches for sustainable environmental monitoring and pollution management.

Keywords: Heavy metal pollution, bioindicators, insects, biomonitoring, environmental pollution, bioaccumulation, ecotoxicology, honey bees

Introduction

Environmental pollution has become a serious global concern due to rapid industrial development, urbanization, mining operations, vehicular emissions, excessive agrochemical use, and improper disposal of industrial and municipal wastes. Among various pollutants, heavy metals are particularly important because of their toxicity, persistence, and ability to accumulate in living organisms (Briffa *et al.*, 2020). Metals such

as lead, cadmium, mercury, arsenic, chromium, and nickel do not degrade naturally and remain in ecosystems for extended periods. Their accumulation in soil, water, plants, and animal tissues creates long-term ecological and human health risks.

Heavy metal contamination affects ecosystem functioning at multiple levels. In soil ecosystems, toxic metals alter microbial activity, reduce nutrient cycling, and affect soil fertility. In plants, they inhibit seed germination, reduce chlorophyll synthesis, disturb photosynthesis, and induce oxidative stress. Aquatic ecosystems are also severely affected because metals accumulate in sediments and subsequently enter food chains through aquatic organisms (Das *et al.*, 2023). Chronic exposure to heavy metals has been associated with neurological disorders, kidney damage, reproductive abnormalities, carcinogenesis, and endocrine disruption in humans (Sall *et al.*, 2020). Traditionally, environmental monitoring mainly depends on physicochemical analysis of soil, water, and sediment samples using sophisticated analytical techniques such as Atomic Absorption Spectrophotometry (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Although these methods provide accurate information regarding total metal concentration, they often fail to indicate the biologically available fraction that directly affects living organisms (Iqbal *et al.*, 2025). This limitation has increased interest in biological monitoring approaches where living organisms are used to evaluate environmental contamination.

Among different biological indicators, insects have emerged as highly effective bioindicators because of their abundance, ecological diversity, short life cycles, rapid response to environmental stress, and sensitivity to pollution (Parikh *et al.*, 2021).

Their ability to accumulate heavy metals from soil, water, plants, and air makes them valuable ecological sentinels for monitoring environmental quality.

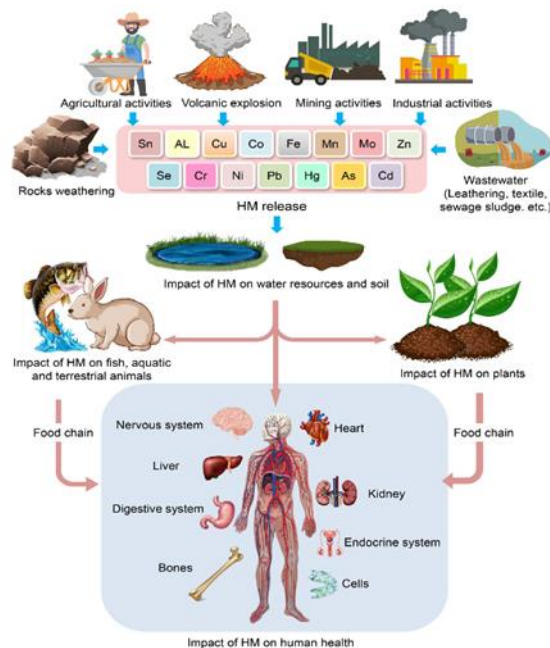


Fig 1. Major sources and environmental pathways of heavy metal contamination in terrestrial and aquatic ecosystems (Abd Elnabi *et al.*, 2023).

Why Insects are Ideal Bioindicators

Insects occupy almost every ecological niche and are present in terrestrial, aquatic, and aerial environments. Their wide distribution and ecological specialization allow them to respond rapidly to environmental changes. Many insects have relatively short generation times, making them suitable for detecting early ecological disturbances (Jan *et al.*, 2024).

Another important advantage is their strong site fidelity. Many insect species remain restricted to localized habitats, allowing researchers to monitor pollution at specific sites with high spatial accuracy. Insects are also comparatively easy to sample, identify, and study under field conditions.

Insects can absorb heavy metals through multiple pathways including:

- Feeding on contaminated plants or organic matter
- Direct contact with polluted soil or sediments
- Absorption through the cuticle
- Uptake from contaminated water
- Inhalation of airborne particulate matter

Because of these exposure routes, insects often accumulate measurable quantities of heavy metals in their tissues and reflect the pollution status of their surrounding environment (Souto *et al.*, 2019).

Table 1. Advantages of Using Insects as Bioindicators

Feature	Importance
High sensitivity	Detect early environmental changes
Rapid life cycle	Quick ecological response
Easy sampling	Cost-effective monitoring
Wide distribution	Suitable across ecosystems
Bioaccumulation ability	Reflect biologically available metals

Mechanisms of Heavy Metal Accumulation in Insects

Heavy metal accumulation in insects occurs through several physiological and biochemical processes. Herbivorous insects mainly ingest metals through contaminated plant tissues, while detritivores and soil dwelling insects consume contaminated organic matter and sediments. Aquatic insect larvae absorb dissolved metals directly from water and sediments (Souto

et al., 2019). Once metals enter the insect body, detoxification mechanisms become active. One of the most important protective mechanisms involves the production of metallothionein, which are metal-binding proteins rich in cysteine residues. These proteins bind toxic metal ions and reduce their harmful effects (Jan *et al.*, 2024).

Insects may also store metals in insoluble intracellular granules, preventing interference with normal metabolic activities. Malpighian tubules assist in excreting excess metals from the body, while some metals are immobilized in the exoskeleton and removed during molting. These physiological adaptations enable insects to survive in polluted habitats and simultaneously act as indicators of contamination levels.

Aquatic Insects as Indicators of Water Pollution

Aquatic insects are widely used for monitoring heavy metal contamination in freshwater ecosystems because they remain in close contact with polluted water and sediments throughout their life cycle. Their sensitivity to environmental disturbances makes them excellent indicators of water quality.

Dragonflies and damselflies (Order: Odonata) are among the most widely used aquatic bioindicators. Their larvae inhabit freshwater systems and accumulate heavy metals from sediments and prey organisms. Studies have shown that odonata larvae (Naiad) effectively indicate contamination by cadmium, lead, and mercury in rivers and wetlands (Jumaat and Hamid, 2023). Chironomid larvae (Diptera: Chironomidae) are also valuable indicators because they inhabit polluted sediments and exhibit strong bioaccumulation potential. Changes in their abundance, morphology, and physiological responses often reflect metal contamination levels in aquatic ecosystems (Jan *et al.*, 2024).

Mayflies, stoneflies, and caddisflies are considered highly sensitive to water pollution and are frequently used in ecological assessment programmes. Their decline or disappearance often indicates deteriorating water quality and ecological imbalance.

Table 2. Important Insect Groups Used as Bioindicators of Heavy Metal Pollution

Insect Group	Habitat	Major Pollutants Monitored
Dragonflies & Damselflies	Aquatic	Cd, Pb, Hg
Chironomids	Aquatic	Heavy metals in sediments
Ground beetles	Terrestrial	As, Cd, Hg
Ants	Soil ecosystems	Industrial metal pollution
Honey bees	Urban & agricultural	Airborne metal contamination
Butterflies	Vegetation ecosystems	Metal deposition

Terrestrial Insects in Pollution Monitoring

Several terrestrial insects have also proven highly effective in assessing environmental contamination.

Ground beetles (Coleoptera: Carabidae) accumulate metals such as arsenic, cadmium, and mercury from contaminated soils and exhibit physiological stress responses including mitochondrial damage and reduced enzyme activity (Conti, 2017). Darkling beetles (*Pimelia latreillei*) show cellular and genetic abnormalities under heavy metal exposure, including micronuclei formation and heat shock protein expression (El-Samad et al., 2021).

Grasshoppers and other orthopteran insects accumulate metals from contaminated vegetation and are useful for evaluating industrial pollution gradients (Azam et al., 2015). Ants are increasingly recognized as reliable indicators because they forage extensively on soil surfaces and accumulate metals in their tissues and nests (Skaldina et al., 2018).

Butterflies are also used in pollution assessment because of their close association with vegetation and sensitivity to environmental disturbances. Recent studies have demonstrated significant metal accumulation in butterfly tissues collected from industrial regions (Pallottini et al., 2023).

Honey Bees as Environmental Sentinels

Honey bees (*Apis mellifera*) are among the most important bioindicators of environmental pollution. Due to their wide foraging range and continuous interaction with air, water, pollen, nectar, and dust particles, bees effectively collect contaminants from surrounding ecosystems.

Heavy metals accumulated in bee tissues, honey, pollen, wax, and propolis provide valuable information regarding environmental contamination (Conti and Botrè, 2001). Honey bees have been successfully used to monitor urban pollution, industrial emissions, vehicular contamination, and agricultural pollutants in many countries.

Because bees forage over large areas, they help generate spatial pollution maps and identify contamination hotspots. Their ecological importance as pollinators further increases their value in environmental monitoring and ecosystem conservation.

Figure 2. Honey bees (*Apis mellifera*) serve as effective bioindicators for monitoring environmental contamination and airborne pollutants.

Modern Approaches in Insect-Based Biomonitoring

Recent technological advancements have significantly improved the effectiveness of insect-based biomonitoring systems. Molecular and biochemical techniques now allow early detection of pollution-induced stress in insects.



Genotoxicity assays such as micronucleus tests, comet assays, heat shock protein analysis, and enzymatic biomarker studies are increasingly used to assess sublethal effects of heavy metal exposure (El-Samad *et al.*, 2021). Advanced analytical instruments such as ICP-MS, X-ray fluorescence spectroscopy, and synchrotron imaging enable precise quantification and localization of heavy metals within insect tissues (Iqbal *et al.*, 2025).

Emerging technologies including Geographic Information Systems (GIS), remote sensing, artificial intelligence, and ecological modelling are also being integrated into environmental monitoring programmes to map pollution hotspots and predict ecological risks.

Challenges in Using Insects as Bioindicators

Despite their considerable advantages, insect-based biomonitoring also faces certain limitations. Different insect species vary in their metal accumulation capacity, ecological behaviour, feeding habits, and tolerance levels, which can influence the accuracy and interpretation of pollution assessment studies

(Parikh *et al.*, 2021). Environmental factors such as soil chemistry, climatic conditions, vegetation type, and seasonal variation may also affect bioaccumulation patterns and ecological responses (Jan *et al.*, 2024).

Interpretation of biomonitoring data therefore requires careful understanding of insect ecology, trophic interactions, and physiological regulation mechanisms. In some cases, analytical studies may involve destructive sampling and sophisticated laboratory procedures, which can increase operational costs and technical complexity (Iqbal *et al.*, 2025). In addition, standardized protocols for insect biomonitoring are still lacking in many regions, limiting large-scale comparison and long-term environmental assessment studies (Souto *et al.*, 2019). Greater interdisciplinary collaboration among entomologists, ecotoxicologists, environmental scientists, and analytical chemists will be necessary to improve the reliability and applicability of insect-based monitoring systems.

Future Perspectives

Future environmental monitoring strategies are expected to increasingly integrate biological indicators with advanced digital technologies. Insects may play a central role in real-time environmental surveillance systems supported by GIS, artificial intelligence, biosensors, and ecological modelling tools. Emerging concepts such as bio-hybrid “cyborg insects” equipped with miniature sensors are also being explored for monitoring pollution in hazardous environments (Bharghavi *et al.*, 2024).

Further research on species specific accumulation patterns, molecular biomarkers, and standardized monitoring protocols will strengthen the application of insects in pollution management programmes. Integrating insect bioindicators with conventional chemical monitoring can provide a more comprehensive

understanding of ecological contamination and environmental health.

Conclusion

Heavy metal pollution continues to pose serious threats to environmental sustainability, biodiversity, and human health across the globe. Conventional chemical monitoring methods alone are often insufficient to assess the ecological impacts and biological availability of toxic metals. In this context, insects provide highly valuable ecological tools for monitoring environmental contamination because of their sensitivity, abundance, ecological diversity, and ability to bioaccumulate pollutants.

Various insect groups including dragonflies, beetles, ants, butterflies, chironomids, grasshoppers, and honey bees have demonstrated immense potential as bioindicators in terrestrial and aquatic ecosystems. Advances in molecular biology, ecotoxicology, and analytical technologies are further enhancing the role of insects in environmental assessment programmes. Integrating insect-based biomonitoring with modern environmental management approaches can contribute significantly to sustainable pollution surveillance and ecological conservation in the future.

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