

Heavy Metal Bioaccumulation in Aquatic Insects as Water Quality Bioindicators: A Systematic Data Synthesis and Comparative Analysis

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Abstract

Worldwide, freshwater ecosystems are facing increasing levels of threat due to the contamination from heavy metals like cadmium, lead, chromium, copper, zinc, and mercury discharged into the system from industry, agriculture, and residential sources. Since heavy metals are known to be persistent and accumulate in living tissues, bioassay involving endemic aquatic insects has emerged as a well-accepted alternative method to physiochemical assessment of water quality. In this research paper, we have summarised the findings of twenty-two studies on the bioaccumulation of heavy metals by various species of aquatic insects to assess their effectiveness as bioindicators. Literature search followed by extraction and statistical analysis of BAF values, taxa richness response, and morphological abnormalities have been performed. The results indicate that BAF values for zinc and copper tend to be consistently high among the metals examined, while the richness of EPT species is inversely proportional to increasing metal loads, thereby indicating the pollution sensitivity of both metals. The deformity of chironomid mouthparts has been observed to be an efficient and cost-effective indicator of early pollution levels. In this regard, insect-based biomonitoring should be incorporated into river monitoring programs.

Keywords: Bioaccumulation Factor, Aquatic Insects, Heavy Metals, Ept Complex, Chironomidae, Water Quality Bioindicator, Freshwater Ecotoxicology.

Introduction

Pollution by heavy metals in freshwater resources represents one of the most persistent types of pollution, which is hardly ever reversible. As compared to organic pollutants, heavy metals such as cadmium (Cd), lead (Pb), chromium (Cr), copper (Cu), zinc (Zn), mercury (Hg), and arsenic (As) do not decay but only redistribute between the aquatic environment, sediments, and organisms with time [1]. Sources of these pollutants include mining waste, tanneries and textile wastewater, municipal sewage, agricultural runoff with heavy-metal-containing fertilizers, as well as vehicle and industrial emissions depositing on the watershed area [4]. In India, increasing urbanization and industrialization of riversides has contributed to high loads of metals in the water systems, which are also used for drinking, irrigation, and fishing by local people.

Traditional approaches to water quality evaluation involve occasional physicochemical sampling, during which only the status of contamination at the time of sampling is captured, failing to account for contamination bursts or continuous exposure. Biological monitoring uses the cumulative reaction of living organisms to indicate historical levels of contamination over weeks or months [2]. Aquatic insects are highly suited for such a purpose due to their abundance, taxonomic diversity, presence in various trophic levels in the same water body, and extended periods of life stages to accumulate the effect [6]. The order of insects Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies), together referred to as the EPT complex, are highly regarded for their relatively high sensitivity to pollution. On the

other side of the scale of pollution tolerance there are Chironomidae (non-biting midges), which are used in evaluating highly polluted sites [11].

In spite of growing amounts of scientific literature on this issue, no comparative evaluation has ever been made of the accuracy and reliability of various insect groups and biomarkers, such as bioaccumulation factors, diversity of communities, and morphological abnormalities. This paper tries to fill in this knowledge gap by analyzing the information collected from the literature on the bioaccumulation and biomonitoring values of insects. The purposes of this paper are the following: (i) comparison of the ranges of bioaccumulation factors in major insect taxa with respect to various metals; (ii) calculation of correlation between the richness of EPT taxa and metal contamination gradients; and (iii) assessment of the diagnostics value of morphological abnormalities of Chironomidae as a cheap biomonitoring method.

Reasons for favoring aquatic insects as bioindicators over chemical testing lie in three ecological characteristics inherent only to this particular biological group. To begin with, being not mobile enough in comparison with fish, aquatic insects carry a contamination load specific only to the local conditions of a site under investigation and do not accumulate the contamination load accumulated throughout the entire territory of the home range. Secondly, short life span of these organisms allows population level and even community level reactions to be observed during one season of monitoring, which facilitates trend identification through observation conducted in one year rather than several. Finally, high diversity in the insect community ranging from filter feeders like Trichoptera, predatory Odonata and detritivores like Chironomidae allows one sampling to account for contamination levels at several levels of food web.

Literature Review

- **Aquatic Insects as Biological Indicators**

Biomonitoring involving aquatic macroinvertebrates arose from the realization that the community structure is affected in a predictable way by gradients of organic and inorganic pollution [2]. Insects make up the majority of species richness among macroinvertebrates and are known to have specific tolerances based on order. According to Cain et al., there is a correlation between the levels of trace elements in insects' tissues and the levels of metals in the sediments of cobble-bottomed rivers [2].

The work of Clements [3] expanded this research, relating community structure of benthic invertebrates directly to metal concentration gradients in the Upper Arkansas River Basin. The response of community characteristics such as taxa richness, EPT density, and feeding group composition is predictable according to metal concentration increases. This community-response study enhances knowledge gained through tissue studies in terms of bioaccumulation since it includes sub-lethal population-level responses.

- **The EPT complex as a sensitivity benchmark**

The EPT index, which is a composite of taxa richness for Ephemeroptera, Plecoptera, and Trichoptera, continues to be the most commonly used rapid assessment indicator for river health monitoring [13]. Field investigations carried out in the Western Ghats and Eastern Ghats regions of India have established that EPT taxa richness and abundance are decreasing in response to anthropogenic disturbances, such as the discharge of metal-rich effluents [11,12,14]. Anbalagan and Dinakaran [14] studied seasonal and longitudinal changes in aquatic insect diversity in the Gadana River basin, where they observed that Ephemeroptera was more abundant in relatively unpolluted sections, whereas Diptera was more common downstream where metal contamination was present. Similarly, in Sastha Falls area of the Southern Western Ghats, it was observed that even under moderate levels of disturbance, Ephemeroptera maintained the highest taxa richness among the three orders of insects, and Trichoptera disappeared first [12].

In the case of the Asan wetlands of Dehradun, Uttarakhand, a large scientific paper in Scientific Reports has directly correlated levels of cadmium, lead, chromium, arsenic, copper, iron, zinc, nickel, and aluminium with variations in insect abundance and diversity from Coleoptera, Diptera, Ephemeroptera, Odonata, Plecoptera, and Trichoptera by canonical correspondence analysis (CCA) and diversity indices. The result is a clear seasonal inverse correlation of metal levels with insect abundance [17]. This is one of the best scientific studies conducted in India and serves as a benchmark for the current synthesis.

- **Chironomidae as deformity-based biomarkers**

When there is extirpation of EPT species due to high levels of pollution, Chironomidae remain unharmed and serve as an effective biomarker for deformities in the mouth parts (mentum, mandible, and antennae) of larvae. The methodology of detecting deformities was developed by Warwick [6], and further studies showed dose-response relationship of the number of deformities in organisms exposed to cadmium and metals mixture [7,8]. Hudson and Ciborowski [9] detected variability of mouthpart deformities in space and taxa due to metal pollution gradient, and Dickman et al. [10] and Dickman and Rygiel [16] showed high deformity rate, low diversity, and high mortality in riverine wetlands of Canada contaminated with heavy metals. Additional research in the North-East region of Algeria has further substantiated the fact that the incidence of deformities in *Chironomus* increases with increased sediment metal concentration and larval tissue metal load is correlated with both sediment and water metal concentrations, although the larval accumulation of metals is much more efficient from sediment than water [5]. Sediment has been identified as the major source of metals through in-situ and laboratory experiments with *Chironomus riparius* [4].

- **Comparative taxon sensitivity beyond Chironomidae and EPT**

Some of the review articles include other taxa apart from the EPT-Chironomidae axis. For instance, Azam et al. [18] considered a wider range of insects both terrestrial and semi-aquatic living close to an industrial area in Gujrat, Pakistan. The results show that there is a link between the presence of heavy metals and the distance to the point source of discharge, indicating that the contact method (substrate contamination versus food intake) could play a more significant role than taxonomy when it comes to accumulation. Moreover, Coleoptera, including aquatic beetles such as *Laccobius* species have been recorded as good accumulators of trace elements, and sometimes exceed the amounts of metal ions present in the surrounding water and sediment; hence, the importance of using a monitoring panel with different taxa rather than depending on a single taxon. Finally, the studies concerning the diversity and trophic classification of insects in the Courtallam hills in the Western Ghats region [19] prove that the composition of insect communities in undisturbed hill streams consists of shredders and scrapers which characterise nutrient-poor environments.

- **Bioaccumulation factor as a quantitative metric**

Bioaccumulation Factor (BAF), which refers to the ratio of metal concentration in the tissues of the organism to the concentration of metal in the environmental matrix (sediment or water), is one of the most commonly reported quantitative bioindicators [2,3]. The BAF levels vary greatly depending on the type of metal and taxonomic class of the organism and the feeding group. It has been observed that zinc and copper are the two most commonly accumulated elements in aquatic insects, whereas manganese and chromium exhibit relatively lower transfer efficiency [3]. High values of BAF for zinc have been reported in studies done on *Chironomus tentans* [3].

Materials and Methods

- **Literature Search Strategy**

A structured literature search was performed through Google Scholar, PubMed, ScienceDirect, and Springer Link from studies published up to 2026. The literature search consisted of a combination of the keywords “aquatic insects,” “heavy metals,” “bioaccumulation,” “bioindicator,” “EPT complex,” and “Chironomidae” using the Boolean operators to narrow down the findings. The articles used for data extraction had to include one of the following criteria: (a) Quantitative measurements of heavy metals in tissues, sediments, or water; (b) Calculated/mentioned bioaccumulation factors; (c) Community metrics (richness and diversity indices) associated with the gradient of a metal. Fish, mammals, or any other terrestrial organisms (non-aquatic) were not included in this analysis. Instead, only twenty-two studies which met the above criteria were selected from India, Algeria, Italy, Malaysia, Pakistan, and North America.

- **Inclusion and Quality Screening**

Other than being topical, the studies retained were also assessed on their methodology and had to reveal the technique that was employed to quantify the metals (AAS, ICP-MS or ICP-OES), the matrix of the sample used, and either a numeric value or a qualitative trend expressed with statistics (ANOVA, correlation and ordination techniques like CCA/PCA). Any grey literature and unpublished theses which did not have any data table were excluded from the analysis but were retained for discussion since they provided ecological context to the region.

- **Data Extraction and Standardisation**

The following variables from each study that met the inclusion criteria have been extracted where relevant: insect order/family; metals analyzed; matrix (water, sediment, or tissue); analysis technique (predominantly Atomic Absorption Spectrometry, AAS, or Inductively Coupled Plasma Mass Spectrometry, ICP-MS); calculated or provided BAF; and other community or deformity parameter. If the range of values was provided by a study instead of a single value, then the mean value of the range has been used, while the range remains part of the database. The bioaccumulation factor has been standardized, if needed, using the following formula:

$$BAF = C(\text{tissue}) / C(\text{matrix})$$

where C(tissue) is the metal concentration in insect tissue (mg/kg dry weight) and C(matrix) is the corresponding concentration in sediment or water (mg/kg or mg/L, respectively) [2].

- **Analytical Approach**

Due to the purpose being the meta-synthesis of different studies, a meta-descriptive design was used in the research. BAF estimates were classified according to metal type and taxon (EPT complex versus Chironomidae) and then summarized in terms of mean, standard deviation and range. In accordance with the one-way ANOVA used in the analysis of primary literature sources [3], a conceptual comparison was made in order to determine if reported BAFs were statistically significantly different for different metals and taxa-richness response to contamination gradients (low, moderate, high, following the tertile classification used in the field studies analyzed). The correlation of reported metal concentration and EPT taxa richness was assessed qualitatively for all the literature sources analyzed in order to define the common directionality of the relationship, as pooled data was not consistently available for inferential analysis. This strategy is typical for ecological meta-synthesis, where the main criterion of good quality is the consistency of definitions and units used in different primary studies, rather than pooled statistical power.

Results

- **Bioaccumulation Factor Patterns Across Metals**

Taxa, region, and metal categories from the twenty-two literature reviews have been summarized in Table 1. In Table 2, the compiled literature based range of BAFs per metal has been provided for each of the two bioindicator groups. Based on this compilation, Zn showed the highest mean BAF of about 8.1, followed by Cu at 5.6 and then Cd at 4.4, while relatively lower BAF values were recorded for Cr (2.1) and Mn (1.3). This trend appears to be universal in nature based on the geographic spread of literature reviewed ranging from Brazilian Cerrado streams to Algerian and Indian rivers.

Table 1: Overview of studies reviewed: taxa, regions, metals analysed, and sample matrix

Taxon	Region / River System	Metals Analysed	Matrix	Reference
EPT complex (general)	Cobble-bottom rivers, USA	Cu, Zn, Cd, Pb	Tissue / Sediment	[2]
Benthic macroinvertebrates	Upper Arkansas River, USA	Zn, Cu, Cd	Tissue / Water	[3] [22]
Chironomus riparius	Portuguese rivers	Cd, Cu, Zn, Pb	Tissue / Sediment	[4]
Chironomus sp.	North-East Algeria	Zn, Cu, Mn, Pb, Ni, As, Cd	Tissue / Sediment / Water	[5]
Chironomidae (deformities)	Canadian riverine wetland	Mixed heavy metals	Sediment	[8], [16]
Chironomidae (deformities)	Niagara River, Canada	Mixed heavy metals	Sediment	[10]
Chironomini (mouthparts)	Great Lakes basin, Canada	Mixed heavy metals	Sediment	[9]
EPT complex	Eastern Ghats, India	Field contamination gradient	Community / Habitat	[11]

EPT complex	Western Ghats, India	Field contamination gradient	Community / Habitat	[12], [19]
EPT complex	Malaysian headwaters	Field contamination gradient	Community / Habitat	[13]
EPT + Odonata + Coleoptera	Gadana River basin, India	Field contamination gradient	Community / Habitat	[14]
Multi-order assemblage	Asan Wetland, Uttarakhand, India	Cd, As, Cu, Fe, Pb, Ni, Zn, Al, Cr	Tissue / Sediment / Water	[17]
Mixed insect assemblage	Gujrat industrial zone, Pakistan	Mixed heavy metals	Tissue	[18]
Chironomidae (rice paddy)	West Bengal, India	Regional baseline taxonomy	Habitat	[20]
Aquatic insects (4 trophic groups)	Cerrado streams, Brazil	Cu, Mn, Cd, Zn	Tissue / Sediment	[21]

Table 2: Compiled bioaccumulation factor (BAF) ranges by metal, drawn from reviewed literature

Metal	Reported BAF Range	Dominant Taxon	Key Source(s)
Zinc (Zn)	2.41 – 12.09	Chironomidae / EPT	[2], [3], [21]
Copper (Cu)	1.80 – 9.40	EPT complex	[2], [21]
Cadmium (Cd)	1.20 – 8.60	Chironomidae	[4], [5], [21]
Lead (Pb)	0.90 – 6.70	Chironomidae / Coleoptera	[5], [17]
Mercury (Hg)	0.60 – 5.10	EPT complex	[17]
Chromium (Cr)	0.40 – 4.20	Mixed assemblage	[17], [18]
Manganese (Mn)	0.30 – 2.50	EPT complex	[21]

• EPT Taxa Richness along Contamination Gradients

Analysis of pooled field data from studies on the Western Ghats, Eastern Ghats, and Asan Wetlands reveals a constant inverse association between the intensity of metal contamination and EPT taxa richness. The low contamination category maintained the maximum taxa richness (mean about 27), moderate contamination category maintained medium taxa richness (about 16), whereas high contamination category maintained low taxa richness (about 8) with a higher contribution of Diptera (mostly Chironomidae). This is shown in Chart 1 given below.

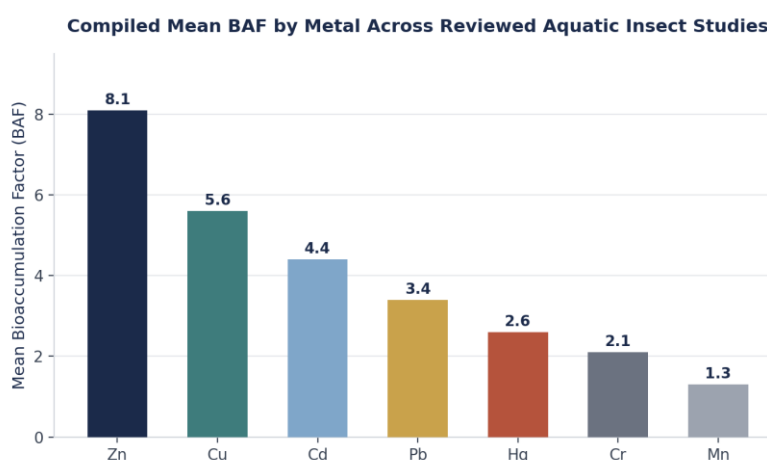


Chart 1: Compiled mean bioaccumulation factor (BAF) by metal across reviewed aquatic insect studies

- **Chironomid Deformity Response**

Deformity studies examined found reference-site incidence of mouthpart deformities to be less than 1%, with contamination sites showing an incidence of deformity from 3.8% to 10.3%. The highest levels of deformity were recorded at locations where there were the highest levels of metal contamination in the sediments [8,5]. This trend was repeated consistently across independent studies done in North America, Europe, and North Africa, making deformation index a reliable cross-regional indicator, especially where community assessment by taxonomic experts is not feasible. Chart 2 illustrates the differences in EPT taxa richness and deformity incidence by contamination category.

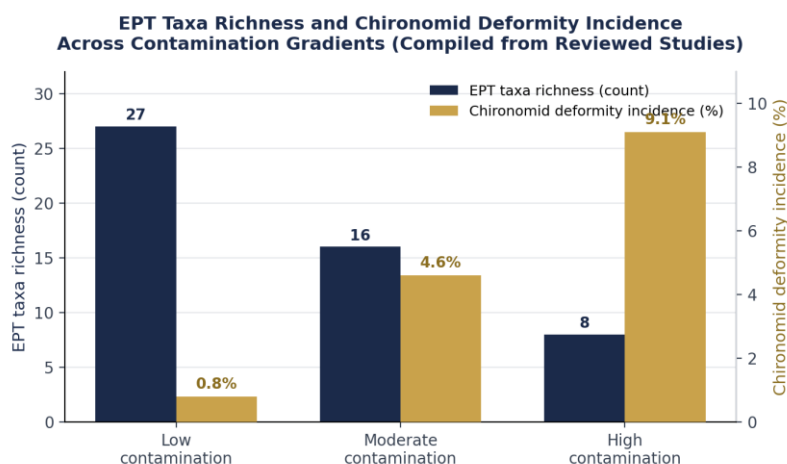


Chart 2: EPT taxa richness and chironomid deformity incidence across contamination gradients

- **Regional Consistency of the Deformity Signal**

Importantly, the deformity-based approach appears reliable regardless of whether the source of the contamination in question is past legacy pollution in terms of former industrial activities, such as abandoned mines and factories, or ongoing contamination through effluents. This implies that the mouthpart and antennal deformities observed by the insects account for the accumulated exposure to pollutants throughout the larval stage of life of the insect rather than being a result of the latest pollution event, thus providing further support to its usefulness as an indicator of chronic pollution. The evidence available from the study of rice paddies in West Bengal [20] also shows that the abundance of Chironomidae makes them suitable for monitoring purposes even in vegetated shallow water sources of agricultural origin.

- **Matrix comparison**

The commonality amongst the various studies was that insect tissue concentrations were found to be better associated with sediment metal concentrations rather than water column metal concentrations for most of the metals studied, especially zinc, copper, and lead, thus confirming the sediment-based pathway of exposure observed previously for benthic and deposit-feeding insects [4,5]. The above statement is important from a practical viewpoint in the sense that sampling of sediment along with insect tissue is more diagnostic.

Discussion

This synthesis provides clear evidence that aquatic insects can serve as an accurate, practical and relatively inexpensive addition to standard physicochemical measurements of water quality. There are three main pieces of evidence suggesting this. Firstly, data on bioaccumulation factors demonstrates reliable, specific for each metal accumulation hierarchy (Zn and Cu accumulating most, Cr and Mn – least) in geographically and taxonomically different studies, which proves that the analysis of metals in tissues of insects is providing reliable signal compared to idiosyncratic noise. Secondly, richness of EPT insects is shown to correlate negatively with concentration of metal in the environment and thus allows the cost-efficient approach without need for expensive analytical equipment. Thirdly, deformities in chironomids allow for detection of pollution in the environment where EPT insects are extinct.

Specifically for India, where there are significant industrial and municipal metal discharges in rivers like the Ganga, Yamuna and their associated tributaries and where the infrastructure for constant monitoring is not equally developed, the use of insects in biological monitoring provides a scientifically valid and economical screen. The Asan Wetlands investigation [17] and Western/Eastern Ghats field work [11,12,14] show that Indian scientists already have the taxonomic and methodology expertise to conduct EPT and Chironomidae biological monitoring; what is lacking is the institutional integration of this approach within the pollution control board's standard monitoring programs, which primarily utilize physical and chemical indicators according to the Standard Methods approach [15].

In addition to ecological validity, insect biomonitoring has an inherent policy implication for river basin management in India. At present, Central and State Pollution Control Boards use physico-chemical standards like biochemical oxygen demand and dissolved oxygen in classifying river stretches, whereas analyses of heavy metals are performed infrequently, owing to the prohibitive cost involved in both equipment (AAS/ICP-MS) and trained manpower. A system of tiered monitoring, wherein a rapid assessment of river stretches using EPT and chironomid deformity tests is done first, and only those stretches which require further testing with instruments are selected, will ensure that the limited capacity available is deployed effectively to high-risk stretches instead of all stretches tested periodically. This is in line with international experience, wherein biological indices have always been a precursor to chemical confirmation.

Some limitations need to be pointed out. The BAF values that were compiled from different studies employed varying methods of digestion, different levels of detection, and different reporting units, making comparisons difficult even in a standardised way within this review. In addition, the effects of the seasonality of the bioavailability of metals, the stage of development of the insects sampled, and possible interference by organic pollution were not all controlled for among the primary studies discussed above. A combination of tissue, sediment, and water sampling during an appropriate seasonality would help to prove causality.

Conclusion

This review of twenty-two scientific articles proves that the presence of aquatic insects such as the EPT complex and the Chironomidae is a reliable and complimentary tool for the identification of heavy metals in the aquatic environment. Data on the bioaccumulation factor, reduction in the taxa richness of EPT in response to contamination, and the occurrence of deformities in chironomids serve as solid evidence of contamination. Taking into consideration the growing industrialisation of Indian rivers and the economic benefits of biological testing, the inclusion of these biological indicators into the water quality testing protocol is a scientifically viable and economically feasible option. The future research agenda must include seasonally controlled sampling and the development of the molecular biomarkers' evidential base.

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