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Role of invertebrates and vertebrates as bioindicators for environmental monitoring

Demi Raut and Gayathri N.
Department of Zoology, MES's D. G. Ruparel College of Arts, Science and Commerce, Senapati Bapat Marg, Mahim, Mumbai

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Correspondence Address:
Demi Raut and Gayathri N.
Department of Zoology, MES's D. G. Ruparel College of Arts, Science and Commerce, Senapati Bapat Marg, Mahim, Mumbai 400016.
Email: gayathri.n@ruparel.edu

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Abstract

Pollution, habitat destruction and climate change contribute to the loss of biodiversity and ecosystem. Environmental health monitoring constitutes a fundamental prerequisite for safeguarding human well-being, economic stability, and ecological sustainability. Rigorous monitoring ensures compliance with regulatory frameworks, including the Restriction of Hazardous Substances (RoHS) and Registration, Evaluation, Authorisation and Restriction of Chemical (REACH). The term bioindicator refers to an organism whose presence, abundance, diversity or physiology serves as an indicator of the ecological state of the environment around them. In the current study the role of zooplanktons, macroinvertebrates and vertebrates in the ecosystem pertaining to their sensitivity to environmental changes are reviewed. Zooplanktons are the prime indicators of nutrients and chemicals in the water bodies. Macroinvertebrates are commonly used in studies concerning fresh water because they are easily collected from one location at a particular time and are sensitive to environmental changes. Amphibians can be considered highly useful bioindicators because of their permeable skin and dual stage life cycle, making them susceptible to various types of pollution. The application of these bioindicators spans across environmental impact assessment, water quality management, pollution control, habitat restoration programmes, and regulatory compliance monitoring thereby offering a cost effective and ecologically meaningful approach to sustaining ecosystem health and informing evidence conservation strategies.

Keywords: *Biomonitors, Eutrophication, Habitat.*

Introduction:

Monitoring environmental health is fundamental to safeguarding human well-being, as the quality of air, water, and soil directly influences population health. The World Health Organization estimates that mitigating environmental risks could prevent nearly 24% of global deaths. Functioning as a critical early-warning system, environmental monitoring enables proactive public health protection through multiple interconnected pathways (1,2). It facilitates disease prevention by detecting emerging threats before clinical manifestation. Systematic tracking of pollutants directly reduces the burden of both acute and chronic illness: air quality monitoring of particulate matter and nitrogen dioxide informs interventions that lower risks of respiratory, cardiovascular, and oncological diseases (3,4). Regular testing of water and food supplies prevent exposure to heavy metals, toxins, and pathogens linked to developmental impairments and mass poisoning events (5–8). Monitoring environmental changes is vital for safeguarding human health and planetary sustainability, shifting management from reactive to proactive (9,10). Biodiversity monitoring reveals ecosystem stress, enabling timely conservation before irreversible tipping points (2,11,12). The term biological indicator (BI), in environmental science, is a living organism like lichens, amphibians, or aquatic macroinvertebrates whose presence, absence or physiological response reflects ecosystems health or pollution stress (6,7,13). While chemical indicators verify parameters like temperature, biological indicators demonstrate actual biological impact whether microbial death or ecological disruption (14–16)

Microorganisms such as bacteria, algae and lichens serve as highly effective bioindicators for monitoring environmental and ecosystem health. Bacteria, owing to their ubiquity and rapid response to environment changes, act as early warning signals for ecological disturbances (13,14). Algae, as a primary producer with short life cycles, respond almost immediately to shifts in water chemistry, with sensitive diatoms indicating good water quality, and for long term heavy metal monitoring (19–22).

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Lichens absorb atmospheric pollutants directly, rendering them particularly reliable indicators of air quality. They are sensitive to sulphur dioxide laden environments, and their heavy metal retention is used to check industrial pollution. Vascular plants, mosses and key animal species further extend the scope of bioindication. Mosses accumulate airborne heavy metals, ozone sensitive plants like white clover exhibit visible leaf damage, and honey bees, dragon fly larvae and apex predators track toxic biomagnification across food chains (23). In the present study, the bioindicative roles of zooplanktons, macroinvertebrates, and amphibians are systematically reviewed with respect to their responsiveness to environmental stressors and ecological significance (14,24–27)

Zooplanktons:

Zooplanktons are microscopic organisms encompassing protists, rotifers, copepods and cladocerans. They serve as highly versatile bioindicators for freshwater quality assessment due to their diverse taxonomic composition. Their community structure is intrinsically linked to environmental variables such as lake surface area, depth, trophic level, temperature, and water colour, making them effective reflectors of environmental stress, thermal changes and ecological status. The size, distribution, and abundance of zooplankton populations correlate strongly with various biotic and abiotic parameters, including pH, alkalinity temperature, dissolved oxygen, transparency, phosphate and chlorine levels. Shifts in species distribution are interpreted as significant signs of changing water status (28–30)

Specific rotifera species such as *Brachionus angularis*, *B. calyciflorus*, *B. diversicornis*, and *Asplanchna* sp. are indicative of eutrophication and high nutrient loads. It was demonstrated that rotifer densities in shallow lakes correlated with elevated inorganic nitrogen (NO_3^- and NO_2^-) (30,31). Similarly, abundances of *Brachionus forficula*, *B. nilsoni*, and *Trichocerca* sp. as strong indicators of eutrophic conditions were identified (30,32). Cladoceran *Daphnia magna* is a recognized sensitive toxicity indicator, particularly for synthetic detergents and its population size is often linked to nutrient availability. Copepods and Ostracods serve as general indicators of water quality status, responding to parameters like dissolved oxygen, phosphate and correlating with broader biotic and abiotic factors. Species such as *Trichocerca cylindrica*, *T. pusilla*, *T. similis*, and *Brachionus forficula* function as temperature indicators (30,33)

High rotifer density and low cladoceran abundance in Parque General Belgrano (PGB) indicated anthropic pollution (30–32,34,35), whereas *Daphnia* presence and higher cladoceran proportions in Reserva Ecológica Ciudad Universitaria (RECU) reflected better water quality. Multimetric zooplankton indices effectively resolved a pollution gradient (PGB < RECU) and responded to trophic stress via taxonomic and functional metrics (36–38).

Zooplankton communities serve as effective bioindicators for eutrophication and heavy metal contamination, with attributes like species richness, diversity, and biomass revealing stress-induced structural and functional changes. Environmental stress triggers an inverse relationship with body size, favoring r-strategist rotifers and opportunistic nauplii while reducing sensitive larger crustaceans (copepods, cladocerans). These predictable community shifts enable zooplankton to function as efficient water quality descriptors for pollution monitoring. Integrating zooplankton assessments into trophic web analyses, emphasizing biological control, provides a comprehensive framework for managing freshwater contamination impacts (15,39).

Eutrophication from land runoff triggers algal blooms and water quality deterioration, favoring pollution-tolerant taxa like *Brachionus* spp., *K. cochlearis*, and *F. longiseta* as reliable bioindicators of eutrophic, polluted waters. Long-term monitoring and nutrient discharge control are essential for managing eutrophication and preserving planktonic community integrity in urbanized Mediterranean waters (32,40). Zooplankton communities effectively discriminate against anthropogenic degradation in Amazonian rivers affected by untreated domestic and industrial effluents, with 149 taxa recorded across impacted and conserved sites. Density and composition varied significantly among rivers, with pollution-tolerant rotifers (*Keratella lenzi*, *Anuraeopsis* sp.) indicating anthropogenically stressed waters, while testate amoebae (*Difflugia* spp.) characterized well-conserved ecosystems. Opportunistic taxa (Cladocera, Rotifera, Cyclopoida) proliferated in eutrophic conditions, whereas sensitive Calanoida declined, reflecting predictable community shifts along pollution gradients. These rapid, taxon-specific responses enable zooplankton to serve as efficient early-warning bioindicators of surface water deterioration. Integrating zooplankton metrics with physicochemical assessments provides a robust framework for monitoring industrial and urban impacts in tropical freshwater systems. Such approaches support proactive environmental management in rapidly developing regions lacking adequate sanitation infrastructure (41).

A two-year study of three altitude-gradient lakes in Himachal Pradesh, India (Rewalsar, Kuntbhyog, Prashar) identified specific zooplankton taxa as reliable bioindicators of water quality and trophic status. The presence of indicator species correlated consistently with seasonal physicochemical parameters, enabling rapid assessment of ecosystem health across varying elevations and morphometric conditions. Rotifers thrive in eutrophic lakes, where high species richness and abundance reflect nutrient-enriched conditions favorable to their proliferation. Their small size and low visibility to predatory fish, combined with tolerance to reduced water transparency, enable rotifers like *Asplanchna*, *Brachionus*, *Filinia*, and *Polyarthra* to serve as reliable indicators of eutrophic status. Due to their rapid life cycles and sensitive community responses, rotifers provide valuable, cost-effective metrics for water quality assessment and conservation planning (42).

A seasonal study of Dodi Tal, a high-altitude Himalayan wetland, recorded 32 zooplankton species dominated by Rotifera (62%), with density peaking in summer and declining during monsoon, reflecting strong coupling with physico-chemical parameters. Sensitive taxa (*Brachionus caudatus*, *B. patulus*, *Cephalodella gibba*, *Colurella obtusa*) serve as early-warning indicators of water quality degradation, while tolerant species (*Ascomorpha ovalis*, *Lecane hastata*, *Alona guttata*, *Bosmina longirostris*, *Daphnia catwaba*, *Acanthocyclops vernalis*, *Arcella vulgaris*) persist under environmental stress (43). Zooplankton community structure in the Lake Peipsi reflects land use intensity and hydrological conditions, with enhanced primary production and water retention fostering diverse feeding guilds and specialized taxa, while urbanization restricts habitat suitability to resilient generalist macrophages (44). Despite limitations, zooplankton-based assessments provide cost-effective, sensitive tools for detecting early-warning signals of water body degradation. Integrating planktonic indicators with physicochemical monitoring offers a complementary, holistic framework for sustainable freshwater ecosystem management in mountainous regions (45)

Macroinvertebrates

Aquatic macroinvertebrates serve as reliable bioindicators for assessing freshwater ecosystem integrity. Within the Planadas-Yeyesa Nature Reserve, macroinvertebrate communities were dominated by pollution-sensitive families including Leptophlebiidae, Elmidae, Libelulidae, and Calamoceratidae, which consistently yielded high Puerto Rico Biological Monitoring Working Party (BMWP-PR) scores (≥5) and low FBI-PR values (≤5), reflecting good water quality and low organic contamination. Pollution-sensitive macroinvertebrates (*Leptophlebiidae, Elmidae*) with high Biological Monitoring Working Party (BMWP) (≥5) and low Puerto Rico Family Biotic Index (FBI-PR) (≤5) dominated the Planadas-Yeyesa Reserve, indicating good water quality, while tolerant taxa (*Thiaridae, Veliidae*) with low BMWP (≤2) and high FBI-PR (≥8) prevailed outside, signaling organic pollution from septic, livestock, and runoff sources. These

results affirm BMWP/FBI utility for assessing degradation gradients (46,47) and support macroinvertebrates as practical bioindicators for watershed management. Aquatic macroinvertebrates represent one of the most extensively validated taxonomic groups for freshwater biomonitoring due to their differential sensitivity to pollution, sedentary nature, ease of sampling, and capacity to integrate environmental stressors over time (34). As bioindicators, macroinvertebrate assemblages reflect both acute and chronic impacts of anthropogenic activities, with pollution-sensitive taxa such as Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) indicating good water quality, while tolerant groups like Chironomidae and Tubificidae signal organic enrichment or contamination (34,48,49). The respiratory adaptations and habitat preferences of macroinvertebrates further enhance their utility; for instance, variations in dissolved oxygen tolerance among taxa provide reliable proxies for assessing hypoxic conditions and trophic status. Mollusks, particularly gastropods and bivalves, are frequently employed as accumulation indicators for heavy metals owing to their limited mobility and high bioconcentration potential; Mahmoud *et al.* (2013) documented a species-specific hierarchy of metal accumulation (*Cleopatra bulimoides* > *Helisoma duryi* > *Bulinus truncatus* > *Biomphalaria alexandrina* > *Physa acuta* > *Bellamya unicolor* > *Theodoxus niloticus*) for Cu, Pb, and Cd, corroborating earlier findings that snails serve as effective sentinels in metal-contaminated systems (34).

Decapods such as crayfish have also been highlighted for long-term industrial monitoring due to their responsiveness to water quality fluctuations and tissue-level pollutant retention. Ojiija *et al.* (2016) reported that relative abundances of Odonata, Hemiptera, Coleoptera, and Diptera could distinguish minimally altered from moderately impacted streams using scoring systems (50,51), while Gautam *et al.* (2014) demonstrated that families like Baetidae (pollution-intolerant) versus Tubificidae and Chironomidae (pollution-tolerant) effectively categorized water quality gradients in Nepalese wetlands, with seasonal dynamics influencing macroinvertebrate density and diversity metrics (e.g., Shannon–Wiener and Pielou indices) (52).

Insects, plants, fungi and higher animals collectively extend the breadth of bioindication across terrestrial, aquatic, and atmospheric environments: honey bees and dragonfly larvae track pesticides and mercury in food webs, mosses and bryophytes accumulate atmospheric heavy metals, ozone sensitive plants like White clover exhibit visible leaf stippling and apex predators such as river otters reveal long-term biomagnification across food chains (6,23). Benthic macroinvertebrates provide sensitive, integrative indicators of freshwater ecosystem health, as demonstrated in Atlantic Forest headwater streams where pollution-intolerant Ephemeroptera (Leptophlebiidae, Leptohyphidae) and Trichoptera (Helicopsychidae, Odontoceridae) signaled oligotrophic, well-oxygenated conditions, while moderately tolerant taxa (Baetidae, Hydroptilidae, Hydropsychidae) reflected resilience to low-level organic input (53,54). In Anchar Lake, *Limnodrilus hoffmeister* density peaked at sewage-impacted sites and correlated negatively with dissolved oxygen and positively with nutrients (nitrate, ammonium, phosphate, total phosphorus), confirming its utility as a pollution-tolerant bioindicator of organic enrichment and eutrophication in temperate freshwater systems (55). In Chilean Mediterranean basins,

macroinvertebrates assessed via a modified Hilsenhoff Index effectively detected agricultural and substrate stress, supporting their use as cost-effective bioindicators for organic enrichment and habitat degradation (56). In Lagos Lagoon, pollution-tolerant Gastropoda and Polychaeta dominated impacted sites, with low diversity correlating with elevated nutrients, heavy metals, and hydrocarbons, while sensitive taxa were excluded (57). Together, these studies affirm macroinvertebrate assemblages as reliable, integrative bioindicators for diagnosing anthropogenic stress and guiding management across diverse freshwater and coastal ecosystems.

Vertbrates

Amphibians (~8,200 species) are ecologically pivotal as secondary consumers and highly sensitive bioindicators, yet ~41% face extinction from habitat loss, pollution, chytridiomycosis, and climate-related stressors. Amphibians serve as effective bioindicators for wetland assessment due to their narrow ecological tolerances, rapid response to disturbance, and cost-effective detectability (36)

A study validating *Phyllomedusa iheringii* tadpoles as bioindicators in the Brazilian Pampa biome revealed significant acetylcholinesterase (AChE) inhibition and oxidative stress markers in individuals from agricultural ponds, suggesting sublethal exposure to organophosphate, carbamate, or glyphosate-based pesticides. The findings endorse *P. iheringii* as a sensitive, endemic sentinel species for monitoring agrochemical impacts in Pampa aquatic ecosystems, while underscoring the need for integrated chemical biological assessments and multi-stressor field studies (58). *Phyllomedusa iheringii* tadpoles exhibit pesticide responsive biomarker alterations in agricultural Pampa ponds, validating their utility as endemic bioindicators of sublethal agrochemical stress in Neotropical freshwater ecosystems. A field study in Turkey's Erzurum Plain validated *Pelophylax ridibundus* as a sensitive bioindicator of agricultural pollution. Frogs from sites with documented nitrate contamination and pesticide use exhibited significantly elevated erythrocyte nuclear abnormalities and severe histopathological alterations in liver (melanomacrophage aggregation, sinusoidal dilatation), lung (alveolar thickening, epithelial hyperplasia), and kidney (tubular necrosis, lymphocytic infiltration) versus reference sites (59). The severity of pathological changes corresponded directly with the degree of agricultural activity, confirming that amphibians reflect sublethal pollutant stress at the tissue and cellular level, making them valuable sentinels monitoring agrochemical impacts on aquatic ecosystems (60,61)

In Malang, Indonesia, amphibian communities at two water sources showed moderate diversity with *Chalcorana chalconota* dominating both sites; higher amphibian density relative to reptiles suggested functional resilience despite anthropogenic

pressures. Reduced predation on amphibians due to snake predators preferentially consuming abundant fish likely facilitated this dominance, consistent with evidence that fish presence can suppress amphibian richness (62) These patterns underscore amphibian assemblages, particularly dominance and predator-prey dynamics, as sensitive, practical bioindicators of freshwater ecosystem integrity in
human-modified tropical landscapes (63).

Fishes

In contrast to the community-level focus of zooplankton, fish are primarily utilized as accumulation indicators for heavy metals and compliance monitoring. They are particularly effective for detecting heavy metal contamination across various tissue types. *Tilapia nilotica* is a key indicator species noted for its ability to accumulate metals such as iron, manganese, nickel, lead, cadmium, and zinc in its tissues. The presence of these metals can result in both lethal and sub-lethal effects, making fish populations critical for assessing the sustainability and health of the aquatic community as a compliance indicator. The assessment of fish health extends to the molecular level through tissue and molecular biomarkers of exposure. Key biomarkers include biliary fluorescent aromatic compounds, vitellogenin, Cytochrome P4501A mRNA/protein, hepatic EROD (ethoxyresorufin-O-deethylase) activity, and metallothioneins (MT), which serve as diagnostic tools at the sub-organism level. Additionally, genetic bioindicators such as *Danio rerio* (zebrafish) are employed to detect mutagenic agents through the analysis of chromosomal damage, bridging the gap between organismal bioindication and cellular biomonitoring. While zooplankton offer depth in trophic status and nutrient monitoring through community ecology, fish provide crucial data on toxic accumulation and genetic integrity within the ecosystem (30).

Conclusion:

Biological indicators play a crucial role in monitoring the health of the environment. Zooplanktons, macroinvertebrates, amphibians, and fish are powerful tools for understanding the health of ecosystems. They are among the most reliable bioindicators for diagnosing problems like organic enrichment and nutrient loading.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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