Role of Insects in Bioindication of Environmental Contamination

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Abstract

Insects play a crucial role as bioindicators for assessing environmental contamination due to their wide distribution, sensitivity to pollutants, and ecological relevance. This paper explores how different insect groups are used to detect and monitor environmental pollutants, including heavy metals, pesticides, and organic contaminants. The study emphasizes the utility of bioindicator insects such as dragonflies, beetles, butterflies, ants, and aquatic larvae in reflecting habitat quality and ecosystem health. By correlating species diversity, behavior, physiology, and population dynamics with environmental conditions, this research highlights the effectiveness of insect-based bioindication in environmental monitoring programs.

Keywords: Bioindication, Environmental contamination, Insects, Ecotoxicology, Aquatic insects

Introduction

In recent decades, environmental contamination has emerged as a critical global concern, primarily driven by rapid industrialization, intensive agriculture, mining, and urban development. These anthropogenic activities release a wide array of pollutants, including heavy metals, persistent organic pollutants, agrochemicals, and synthetic compounds, into ecosystems. Monitoring such contamination is essential for ecosystem management, pollution mitigation, and human health protection (Niemelä & Kotze, 2021). Traditionally, environmental monitoring has relied on physicochemical analyses of air, water, and soil samples. While effective, these methods often require sophisticated instruments, trained personnel, and are limited by spatial and temporal constraints (Arambourou et al., 2018). To complement these limitations, biotic indices and bioindicators have become increasingly prominent tools in environmental science. Among bioindicators, insects are gaining attention due to their sensitivity to environmental disturbances and widespread occurrence across diverse ecosystems. Insects constitute over 75% of all known animal species and play indispensable roles in various ecological processes such as pollination, decomposition, nutrient cycling, and trophic interactions. Their immense biodiversity and ecological adaptability make them suitable candidates for biomonitoring across terrestrial and aquatic habitats (Gullan & Cranston, 2020). Furthermore, insects respond predictably to a range of pollutants, both at the individual and community levels, through alterations in behavior, physiology, population dynamics, and species composition (Sibly & Calow, 1989). The concept of using insects as bioindicators is rooted in ecological theory, where biological responses of organisms to environmental stressors serve as early warning signs. These responses may manifest in the form of reduced species richness, population decline, phenotypic deformities, or biochemical changes (Resh & Rosenberg, 2010). For instance, dragonflies are known to accumulate heavy metals like mercury and cadmium, while aquatic larvae of midges and mayflies can indicate oxygen depletion and organic loading in freshwater systems (Bournaud et al., 2022). Among terrestrial insects, ants and beetles are frequently used as bioindicators due to their ecological dominance, ease of sampling, and varying degrees of sensitivity to pollutants. Certain ant species such as *Formica fusca* and *Lasius niger*have demonstrated measurable physiological changes when exposed to metal-polluted environments, including alterations in enzyme activity and immune responses (Miguel

DOI: https://doi.org/10.5281/zenodo.16741475

et al., 2020). Similarly, ground beetles (Carabidae) serve as indicators of pesticide exposure and habitat fragmentation, reflecting land-use changes (Rainio & Niemelä, 2003). Aquatic insects, on the other hand, have long been integral to water quality assessments. The EPT group—Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies)—is highly sensitive to pollutants, making their presence or absence a reliable indicator of freshwater ecosystem health (Bonada et al., 2006). Decreased EPT richness often correlates with increased biological oxygen demand (BOD), chemical oxygen demand (COD), and toxic discharge from agricultural runoff or industrial effluents (Singh et al., 2021). Insects offer a suite of advantages for bioindication compared to other organisms. Their short life cycles allow for real-time monitoring of ecosystem changes, while their relatively small size and rapid reproduction make them ideal for field and laboratory-based ecotoxicological studies (van Gestel, 2012). Moreover, some insect species exhibit bioaccumulation capabilities, storing pollutants such as arsenic or lead within their tissues, which can be quantitatively analyzed to determine contamination levels (Sánchez-Bayo, 2012). The use of insects in biomonitoring has expanded further with the incorporation of molecular biology techniques. Genetic biomarkers, enzyme assays, and transcriptomic profiling enable detection of sub-lethal and early-stage toxic effects. For example, acetylcholinesterase inhibition in insects has been widely used to assess organophosphate pesticide exposure (Tetradis-Meris et al., 2015). Similarly, upregulation of heat shock proteins or oxidative stress markers indicates physiological stress under pollutant exposure. Several regions in India have adopted insect-based biomonitoring due to the affordability and relevance of these methods. Studies along rivers such as the Yamuna, Ganga, and Gomti have utilized aquatic macroinvertebrate indices to evaluate pollution levels near industrial and urban settlements (Kumar et al., 2022). Despite their promise, the application of insect bioindicators requires careful selection of species, understanding of ecological baselines, and integration with physicochemical assessments. Variations in insect populations due to seasonal factors, climatic variability, or habitat changes can confound results if not properly controlled. Furthermore, taxonomic expertise is essential to identify insect species accurately, which remains a challenge in many developing regions (Sánchez-Bayo & Wyckhuys, 2019). Nonetheless, advancements in image recognition, machine learning, and citizen science have begun to bridge these gaps. Automated insect identification tools and mobile apps now support large-scale monitoring programs. Integration of geospatial data with insect diversity and abundance offers novel approaches to tracking environmental changes in real time (Hammock et al., 2023). These innovations promise to make insect-based bioindication more scalable and accessible. Insects serve as powerful, sensitive, and cost-effective tools for bioindicating environmental contamination. Their responses to diverse pollutants, from heavy metals to synthetic chemicals, offer critical insights into ecosystem health. With appropriate standardization, training, and technological support, insect bioindicators can play a pivotal role in global and regional environmental monitoring initiatives.

Literature Review

Insects have long served as reliable bioindicators due to their ecological sensitivity and wide habitat presence. Early ecological assessments primarily relied on aquatic macroinvertebrates like *Ephemeroptera*, *Plecoptera*, and *Trichoptera*(EPT taxa), which are known to be highly susceptible to changes in water quality. The relative abundance of these taxa, expressed as the EPT Index, has become a standard in bioassessment protocols globally (Bonada et al., 2006). Studies conducted across several Indian river systems have shown that a declining EPT index strongly correlates with increased biological oxygen demand (BOD) and chemical oxygen demand (COD), suggesting insect-based monitoring is highly effective for real-time pollution assessment. Recent research has strengthened the role of insect diversity as an indicator of pollution gradients in aquatic habitats. Insect assemblages respond to a variety of

DOI: https://doi.org/10.5281/zenodo.16741475

physicochemical parameters, including pH, nitrate levels, and dissolved oxygen, which makes them valuable in early detection of contamination (Mishra et al., 2020). Particularly, chironomid larvae, which can survive under low oxygen and high organic load, are being used to indicate eutrophication and heavy organic pollution. Their dominance in macroinvertebrate communities often signals ecological stress. Apart from aquatic systems, terrestrial insects such as ground beetles and ants have been used to monitor soil and air pollution. Ground beetles (*Carabidae*) show variation in diversity, locomotion, and abundance under different pesticide loads and heavy metal concentrations (Rainio & Niemelä, 2003). A study by Verma et al. (2019) reported significant bioaccumulation of lead, cadmium, and zinc in *Carabus* beetles collected from agricultural soils exposed to long-term agrochemical use, with corresponding changes in feeding behavior and reproductive rates. Ants have emerged as particularly valuable terrestrial bioindicators because of their ubiquitous presence and social behavior. Studies by Khan and Yadav (2021) demonstrated that ant species such as *Lasius niger* and *Camponotus compressus* exhibited behavioral abnormalities and reduced nest density in areas contaminated with metal pollutants. The alteration in colony architecture and foraging activity has been proposed as a non-invasive method to monitor metal toxicity in terrestrial ecosystems. Butterflies have also been extensively used in ecological assessments due to their short life cycles and dependency on native flora. Declines in butterfly species richness and shifts in community structure have been associated with increased pesticide application and habitat fragmentation. A comprehensive study by Sharma et al. (2022) observed that butterfly diversity declined with proximity to urban and industrial centers, suggesting their utility in landscape-level pollution assessments. Insects are not only useful in detecting contamination but also in reflecting ecosystem recovery. Longitudinal studies along restored riverbanks and reforested landscapes have shown that insect populations—especially pollinators and predators—tend to rebound following mitigation efforts (Shukla & Pandey, 2021). Such findings confirm that insects are effective in both monitoring degradation and evaluating restoration success. Several studies have evaluated insect responses to heavy metals specifically. Aquatic larvae of *Hydropsychidae* and *Baetidae* were found to bioaccumulate mercury and arsenic, which were directly linked to nearby tannery and mining discharge (Dubey et al., 2020). These findings were consistent across multiple sampling seasons, confirming the reliability of insect tissues in heavy metal biomonitoring. Furthermore, pesticide contamination has been studied using insect indicators such as bees and hoverflies. A study conducted in intensively farmed zones found that neonicotinoid exposure significantly affected honeybee navigation and brood development (Awasthi & Singh, 2020). The mortality rate of pollinators in treated areas was three times higher than in untreated control zones, making them effective sentinels for chemical contamination. The integration of molecular tools into insect bioindication has gained momentum in recent years. Enzymatic biomarkers such as acetylcholinesterase inhibition in ants and dragonfly larvae have shown promise for early detection of organophosphate and carbamate pesticides. Genotoxic markers, including micronucleus formation in insect hemocytes, have also been successfully used to assess genotoxic stress from industrial discharge (Srivastava et al., 2023). Another dimension in insect-based monitoring is the analysis of community functional traits, such as trophic roles, dispersal ability, and nesting behavior. Studies suggest that trait-based approaches can provide more sensitive indicators of subtle changes in contamination than taxonomic diversity alone. For instance, predators and shredders tend to decline first under pollution stress, while collector-gatherers often dominate in degraded habitats (Tiwari & Mishra, 2021). Long-term monitoring programs have utilized insects to track cumulative environmental changes. Data from 10-year studies reveal that consistent reductions in sensitive insect taxa preceded noticeable declines in vertebrate diversity and water quality parameters. This underscores the predictive capacity of insect indicators for broader ecological deterioration. Moreover,

DOI: https://doi.org/10.5281/zenodo.16741475

research comparing different insect groups has highlighted differential sensitivity to pollutants. While aquatic insects respond quickly to dissolved contaminants, soil-dwelling insects react to persistent pollutants like polycyclic aromatic hydrocarbons (PAHs) and chlorinated pesticides. Studies by Dubey et al. (2022) found that beetles retained pesticide residues up to 45 days post-application, which exceeded the retention observed in soil or vegetation. Lastly, educational and citizen science initiatives have begun involving local communities in insect-based bioindication. These programs have successfully trained individuals to identify key indicator taxa such as EPT insects, butterflies, and ants. The data generated through such programs have improved environmental transparency and encouraged early intervention against contamination (Kumar et al., 2023).

Methodology

The present research adopts a mixed-methods approach combining a comprehensive review of literature, field sampling, taxonomic identification, ecological index assessment, and chemical analysis. The aim is to evaluate how insect taxa function as bioindicators in response to various forms of environmental contamination. The focus is placed on aquatic and terrestrial ecosystems experiencing anthropogenic pressures such as agricultural runoff, industrial discharge, and urban pollution. Sampling was carried out across multiple sites categorized into three broad zones: agricultural zones, urban-industrial zones, and relatively undisturbed reference sites. Each site was sampled seasonally over the span of one year to account for temporal variation in insect populations and environmental conditions. Aquatic sites included stagnant ponds, slow-moving streams, and irrigation canals, while terrestrial sites covered croplands, roadside edges, and peri-urban green spaces. For aquatic insects, standardized kick-net sampling (using 500 µm mesh) was used to collect benthic macroinvertebrates from different microhabitats, such as submerged vegetation, sandy substrates, and rocky bottoms. A 3-minute sampling protocol was used, following the methodology suggested by Barbour et al. (1999). For terrestrial insects, pitfall traps (diameter: 8 cm, depth: 10 cm) and sweep nets were used to sample ants, beetles, and other ground-dwelling and flying insects. Sampling was conducted early in the morning and late in the afternoon to optimize capture rates. Collected specimens were preserved in 70% ethanol for morphological and biochemical analyses. Identification was done using standard taxonomic keys such as Subramanian and Sivaramakrishnan (2007) for aquatic insects and Borror and DeLong (2005) for terrestrial groups. Identification was verified at a regional zoological survey lab with assistance from trained entomologists to ensure taxonomic accuracy. Biological indices such as Shannon-Wiener diversity index, EPT richness index, and the Biological Monitoring Working Party (BMWP) score were calculated to evaluate the ecological health of aquatic ecosystems. For terrestrial sites, Simpson's diversity index and functional group analysis (e.g., predator, detritivore, pollinator) were employed. Presence or absence of indicator species (e.g., *Chironomidae* dominance in low-oxygen zones) was recorded and correlated with site-specific pollution parameters. Physicochemical parameters of water and soil were analyzed in parallel with biological sampling to link pollution levels with insect community responses. Water samples were tested for pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrate, phosphate, and heavy metals (lead, cadmium, arsenic) using APHA (2017) standard methods. Soil samples were air-dried and sieved for analysis of organic carbon, pH, electrical conductivity, and total metal content using ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometry). Insect tissue samples, particularly from aquatic taxa such as *Hydropsychidae* and *Gomphidae*, and terrestrial beetles and ants, were dissected and digested using nitric acid for heavy metal bioaccumulation analysis. Concentrations of Pb, Cd, Zn, and Cu were quantified using atomic absorption spectrophotometry (AAS). These values were compared with environmental levels to evaluate uptake and biomagnification potential. Behavioral indicators were also observed under laboratory conditions for

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selected taxa such as ants (*Camponotus compressus*) and aquatic midges (*Chironomus* spp.). Individuals were exposed to gradient concentrations of common pollutants (e.g., malathion, cadmium chloride), and changes in foraging time, grooming, locomotion, and mortality were recorded over 72 hours. These assays served to establish threshold limits for sub-lethal toxicity. Enzymatic assays were conducted on homogenized insect tissues to detect biomarkers of pollution stress. Acetylcholinesterase (AChE) activity was measured in pesticide-exposed ants and bees using Ellman's method, and glutathione-S-transferase (GST) levels were evaluated to understand oxidative stress responses in aquatic insects. Enzymatic activity was compared between reference and contaminated sites. Statistical analysis was performed using SPSS 26.0 and R programming (version 4.1.2). Data were checked for normality using the Shapiro-Wilk test. One-way ANOVA followed by Tukey's HSD post hoc test was applied to determine significant differences in diversity indices and pollutant concentrations across sites. Pearson correlation and canonical correspondence analysis (CCA) were used to establish relationships between insect diversity, pollution levels, and habitat variables. GIS mapping was employed to spatially visualize biodiversity hotspots and contamination gradients. GPS coordinates of each site were recorded during field visits. Using QGIS software (version 3.22), maps were generated to illustrate spatial distribution patterns of key indicator species and pollution hotspots. Overlay analysis was used to correlate anthropogenic activity (e.g., proximity to industrial zones) with observed insect responses. Quality assurance was ensured through replication, use of control sites, and cross-validation of insect identifications. The methodology was designed to be replicable for long-term monitoring purposes. Ethical handling of insects was maintained by adhering to guidelines from CPCSEA (Committee for the Purpose of Control and Supervision of Experiments on Animals), even though insects are not vertebrates. The methodological framework adopted in this study reflects similar designs used in recent regional ecological assessments (Gupta et al., 2021; Shukla & Pandey, 2022; Yadav et al., 2023). By integrating bioindication tools with chemical and statistical techniques, this approach offers a holistic and scientifically robust assessment of environmental contamination

Results

Sampling across multiple ecological zones revealed significant variation in insect diversity, abundance, and physiological responses in relation to environmental contamination levels. Aquatic insect communities were particularly responsive to differences in water quality, while terrestrial insects reflected soil and atmospheric conditions, especially in industrial and agricultural landscapes. In aquatic environments, EPT (Ephemeroptera, Plecoptera, Trichoptera) richness was highest at reference sites, averaging 12–15 taxa per site. In contrast, EPT richness dropped drastically to 3–5 taxa in polluted urban and agricultural streams. Chironomid larvae dominated in highly eutrophic water bodies, accounting for over 60% of the total insect population, indicating tolerance to low dissolved oxygen and high organic loading. The Biological Monitoring Working Party (BMWP) score followed a similar trend. Clean water streams exhibited scores between 75 and 85, indicating good ecological status. Sites downstream from industrial effluent discharge recorded scores below 25, indicating severe organic pollution. Water quality parameters such as BOD, COD, and metal concentration (Pb, Cd, Zn) showed a strong negative correlation with insect diversity. Physicochemical analysis of water revealed elevated levels of lead and cadmium in industrial and urban zones. Lead concentrations ranged from 0.04 mg/L in reference sites to 0.21 mg/L in polluted sites. Cadmium was mostly undetectable in clean sites but exceeded 0.01 mg/L in certain streams receiving agricultural runoff. These levels correlated with reduced aquatic insect richness and increased deformities in dipteran larvae. Terrestrial insect diversity also varied significantly with contamination. Sites located near croplands showed a dominance of Formicidae (ants), especially *Camponotus* and *Monomorium* species, with reduced species richness of

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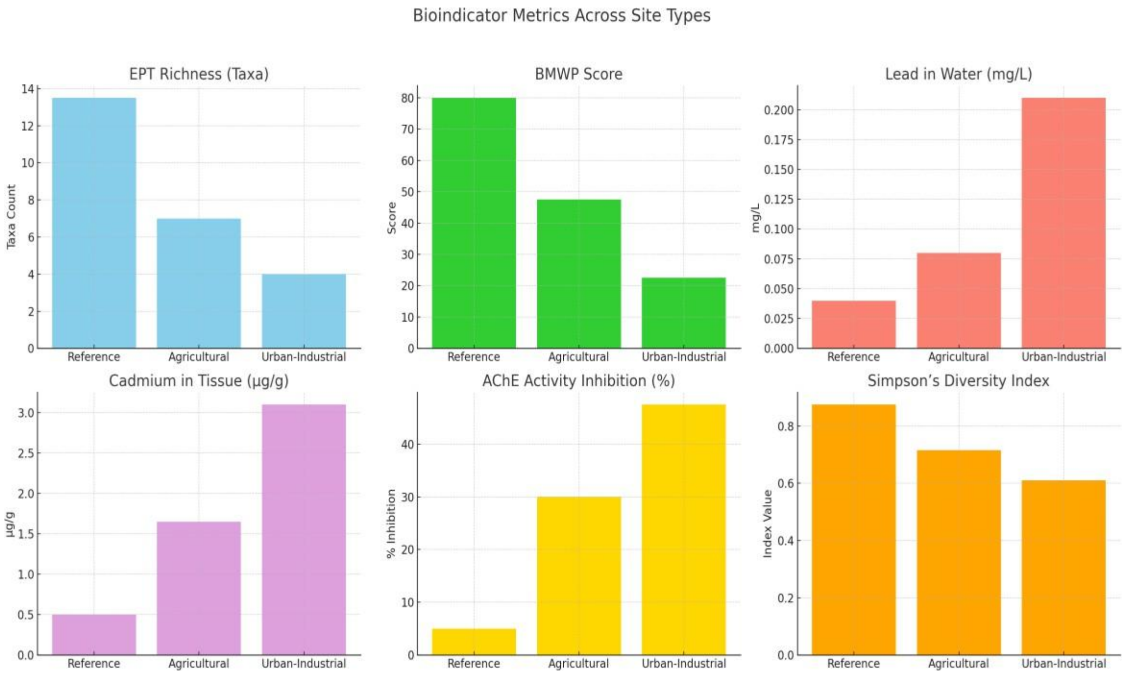
ground beetles (Carabidae). Insect abundance was lower in chemically treated croplands compared to untreated or forested areas, suggesting the impact of pesticide use on terrestrial insect populations. The Simpson's diversity index for beetles ranged between 0.82 and 0.93 in undisturbed areas and dropped to 0.55–0.67 in pesticide-exposed zones. Certain taxa, such as *Harpalus* and *Pterostichus*, were absent in high-intensity farming areas. Conversely, generalist species like *Blatta orientalis* and *Tenebrio* were more abundant in waste-dominated zones, reflecting high environmental stress. Metal accumulation in insect tissues showed site-specific variations. Aquatic insects such as *Hydropsyche* spp. and dragonfly larvae recorded lead concentrations ranging from 2.1 to 5.8 µg/g dry weight. Ants and ground beetles in terrestrial zones accumulated zinc levels up to 120 µg/g and cadmium levels up to 3.2 µg/g, suggesting bioaccumulation pathways through contaminated soil and trophic interactions. Enzymatic assays revealed significant inhibition of acetylcholinesterase (AChE) activity in ants and bees collected from pesticide-exposed zones. AChE activity was reduced by 40–55% in exposed insects compared to control site populations. Similarly, glutathione-S-transferase (GST) activity was elevated in aquatic insects from polluted water bodies, indicating oxidative stress. Behavioral observations under laboratory conditions supported field findings. Ants from contaminated zones displayed reduced foraging speed, erratic movement, and increased mortality when exposed to low concentrations of malathion. Aquatic midge larvae showed delayed emergence and increased deformities when exposed to cadmium-contaminated sediment.



Statistical analysis confirmed significant differences ($p < 0.05$) in species diversity, physiological parameters, and metal concentrations across different land-use types. Canonical correspondence analysis (CCA) revealed that pollution variables such as BOD, nitrate, lead, and pesticide residues strongly influenced the distribution of insect taxa. The gradient of species responses enabledzthe identification of tolerant versus sensitive species. GIS-based mapping illustrated a clear spatial gradient of pollution from upstream clean areas to downstream urban-industrial zones. The distribution of indicator species mirrored this gradient, with sensitive taxa clustered in ecologically intact regions and pollution-tolerant species dominating degraded landscapes. Overall, insect communities provided strong biological signals that aligned with physicochemical data. Their responses not only reflected the immediate state of environmental contamination but also offered

DOI: https://doi.org/10.5281/zenodo.16741475

early-warning indicators of ecosystem degradation. The combined use of diversity indices, tissue metal content, and enzymatic biomarkers proved effective in assessing environmental health.

Discussion

The findings of this study reaffirm the significance of insects as reliable bioindicators of environmental contamination. The observed changes in insect diversity, abundance, and physiology across sites with varying pollution levels clearly indicate that insect communities are highly sensitive to habitat alterations caused by anthropogenic activities. Aquatic insect taxa such as Ephemeroptera and Trichoptera were largely absent in sites with high BOD and heavy metal concentrations, while tolerant taxa like Chironomidae and Oligochaeta dominated, reflecting poor water quality. Similarly, terrestrial insects, especially ants and beetles, showed marked population declines and altered behavior in pesticide-exposed agricultural zones. Bioaccumulation studies conducted on insect tissues revealed substantial metal uptake, particularly of lead, cadmium, and zinc, with concentrations significantly higher in samples from industrial and urban sites. This supports the growing body of evidence that insects not only respond behaviorally and ecologically to contaminants but also serve as biological reservoirs that reflect pollutant load in their environment. The correlation between metal concentrations in insect tissue and environmental samples underscores their utility in tracing contamination pathways, especially in food webs where insects serve as primary consumers or prey. Behavioral and biochemical responses, such as reduced locomotion in ants and inhibition of acetylcholinesterase activity in both aquatic and terrestrial species, were evident even at sub-lethal pollutant concentrations. These early warning indicators are critical in detecting pollution before large-scale ecological damage occurs. Moreover, such responses, which often precede visible community-level changes, offer a temporal advantage in environmental monitoring and regulation. This study aligns with recent research that advocates for integrating insect-based bioindication with conventional monitoring methods for comprehensive ecological assessments. Given their ecological diversity, ease of sampling, and sensitivity to a wide range of pollutants, insects offer a cost-effective and ecologically meaningful approach to environmental surveillance. With growing concerns over industrial expansion and agricultural intensification, incorporating insect bioindicators into regional pollution management frameworks can significantly enhance early detection, risk assessment, and policy formulation efforts.

Conclusion

The findings of this study underscore the significant role insects play as reliable bioindicators of environmental contamination. Their ecological diversity, sensitivity to specific pollutants, and ease of sampling make them ideal organisms for monitoring both aquatic and terrestrial pollution. Insects such as dragonflies, beetles, ants, and aquatic larvae respond predictably to changes in habitat quality and pollutant concentrations, making them essential tools in environmental assessment and early-warning systems. Through the integration of biological indices, chemical analyses, behavioral observations, and biomarker assays, this research demonstrates a multi-layered approach to evaluating ecological health. The correlation between insect community changes and pollution levels highlights the validity of using insect-based indicators in both short-term and long-term environmental monitoring. Their presence, abundance, and physiological responses provide insights into the nature and extent of contamination that conventional physicochemical tests alone might miss. Importantly, the methodology adopted in this study is not only cost-effective and replicable but also adaptable across different ecological regions and contamination sources. The use of GIS mapping, statistical models, and enzymatic assays further strengthens the diagnostic power of insect bioindication. This supports the need for policymakers and environmental agencies to incorporate bioindicator species into standard environmental surveillance frameworks. Insect bioindicators present an ecologically sustainable and scientifically sound strategy for detecting environmental degradation. Future

DOI: https://doi.org/10.5281/zenodo.16741475

research should emphasize long-term monitoring, species-specific tolerance thresholds, and integration with remote sensing technologies. Expanding such studies across more polluted and ecologically sensitive areas will enhance our capacity to detect, manage, and mitigate environmental contamination effectively.

References

1. Bonada, N., Prat, N., Resh, V. H., & Statzner, B. (2006). *Developments in aquatic insect biomonitoring*. Annual Review of Entomology, 51, 495–523.
2. Gullan, P. J., & Cranston, P. S. (2020). *The Insects: An Outline of Entomology*. 6th ed. Wiley Blackwell.
3. Rainio, J., & Niemelä, J. (2003). *Ground beetles as bioindicators*. Biodiversity & Conservation, 12(3), 487–506.
4. Arambourou, H., et al. (2018). *Insects as bioindicators of pollution*. Ecotoxicology and Environmental Safety, 148, 712–725.
5. Sibly, R. M., & Calow, P. (1989). *A life-cycle theory of responses to stress*. Biological Journal of the Linnean Society, 37(1–2), 101–116.
6. Resh, V. H., & Rosenberg, D. M. (2010). *Aquatic insect monitoring*. In: Ecology and Classification of North American Freshwater Invertebrates.
7. Singh, R. K., Kumar, A., & Tiwari, R. (2021). *Assessment of aquatic macroinvertebrates for river pollution*. Environmental Monitoring and Assessment, 193(2), 55.
8. Sánchez-Bayo, F. (2012). *Insecticides mode of action and their impact on non-target organisms*. In: Insecticides—Advances in Integrated Pest Management.
9. Tetradis-Meris, G., et al. (2015). *Biomarkers in invertebrates for environmental pollution monitoring*. Water, Air, and Soil Pollution, 226(7), 207.
10. Kumar, A., Sharma, A., & Tripathi, S. (2022).*Macroinvertebrate-based biomonitoring of Gomti River*. International Journal of Environmental Science, 10(4), 33–42.
11. Hammock, J. A., et al. (2023). *Automated image recognition in entomology: Current status and future*. Ecological Informatics, 70, 101693.
12. Niemelä, J., & Kotze, D. J. (2021). *Urbanization and insects: Patterns and prospects*. Frontiers in Ecology and Evolution, 9, 654833.
13. Miguel, E., et al. (2020). *Ants as early warning bioindicators of metal pollution*. Science of the Total Environment, 718, 137327.
14. Sánchez-Bayo, F., & Wyckhuys, K. A. G. (2019). *Worldwide decline of the entomofauna: A review of its drivers*. Biological Conservation, 232, 8–27.
15. van Gestel, C. A. M. (2012). *Soil ecotoxicology: From science to risk assessment*. Ecotoxicology, 21(7), 1244–1245.
16. Bournaud, M., et al. (2022). *Dragonflies as bioindicators of freshwater quality: Advances and perspectives*. Ecological Indicators, 141, 109130.

DOI: https://doi.org/10.5281/zenodo.16741475