International Journal of Pharmaceutical Research and Applications
Volume 9, Issue 6 Nov - Dec 2024, pp: 1142-1153 www.ijprajournal.com ISSN: 2456-4494

Insects as Indicators of Environmental Pollution: A Tool for Ecosystem Assessment

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Date of Submission: 15-12-2024 Date of Acceptance: 25-12-2024

ABSTRACT
Bioindicators, encompassing a diverse array of organisms such as plants, plankton, animals, and microbes, provide valuable insights into ecosystem health and environmental fluctuations.Advances in environmental contamination research have highlighted the potential of bioindicators as sensitive and effective tools. Identifying species that can accurately indicate environmental disruptions and their effects on biodiversity is the core focus of bioindicator research. This review focuses on the role of insects as a valuable resource for assessing environmental contaminants, exploring their potential in detecting and monitoring pollutants. Insects are particularly suited for assessing the impacts of anthropogenic activities on ecosystems due to their proximity to toxic elements in soil, water, and air, which facilitates the detection of environmental pollutants.As key indicators of environmental changes, insects have been the central focus of our study, particularly in monitoring soil, water, and air quality. The majority of insects, such as beetles, ants, honeybees, and butterflies, are crucial biological indicators in this study, as they are highly sensitive to environmental changes and effective in monitoring pollutants.
Keywords: Bioindicators, insects, pollution

I. INTRODUCTION

The rapid expansion of human populations has led to alarming changes in natural environments worldwide over the past few decades. Globally, the consequences of these environmental changes are far-reaching,compromising ecosystem resilience, biodiversity and human health [1].Comparative assessments of pollution's effects on morbidity and mortality indicate that it remains a paramount risk factor for global health, with impacts comparable to those of tobacco use[2]. According to the World Meteorological Organization (WMO), the global average temperature has increased by approximately one degree Celsius since the pre-industrial era. As reported by the Intergovernmental Panel on Climate Change a statistically significant warming trend is evident over the past three decades, with the 2000s exhibiting the highest temperatures [3]. Effective ecosystem management and prediction rely on the implementation of environmental monitoring strategies to detect and mitigate the impacts of contamination. Biomonitoring plays a crucial role in assessing environmental contamination by utilizing organisms to detect pollutants in air, waterand soil.The term “bioindicator” refers to a species or a group of species that represents the abiotic or biotic state of the environment. It illustrates how environmental change affects a habitat, community, or ecosystem and indicates whether that change has a positive or negative influence [4]. Bioindication is an essential tool in ecosystem management, facilitating the integration of biological information into decision-making frameworks to promote ecosystem sustainability.The application of bioindicators is crucial for predicting the natural state of a region and assessing the degree of contamination, enabling informed decision-making[5].Bioindicators offer several benefits, including the assessment of biological impacts, monitoring of pollutant interactions, early detection of toxin effects, ease of monitoring, and cost-effectiveness, making them a valuable tool in environmental monitoring.

Numerous studies have demonstrated that various living organisms exhibit heightened sensitivity to environmental changes, which can disrupt critical biological processes, including metabolism, growth, and reproduction[6].Insects, as key components of terrestrial, aquatic, and atmospheric ecosystems, offer a unique perspective on the ecological effects of human activities, making them as valuable bioindicators in environmental monitoring and assessment[7].To

International Journal of Pharmaceutical Research and Applications
Volume 9, Issue 6 Nov - Dec 2024, pp: 1142-1153 www.ijprajournal.com ISSN: 2456-4494

elucidate the complex relationships between biodiversity changes and ecosystem function, taxonomic, behavioural, and environmental studies must be conducted in tandem, providing a comprehensive understanding of the implications of biodiversity shifts.The purpose of this review study is to give an overview of the main insect bioindicator groups and their functions in various ecosystems.

Classification of bioindicators

Bioindicators offer a valuable tool for elucidating the complex relationships between environmental factors and ecosystem health, providing critical insights for the management and conservation of ecosystems.The integration of bioindicators into biomonitoring frameworks is being actively promoted by organizations like the International Union for Conservation of Nature, highlighting their potential to inform conservation and management strategies. Bioindicators can be classified into three distinct categories: environmental, ecological, and biodiversity indicators, providing a framework for understanding their various applications and backgrounds[8].The taxonomic classification of bioindicators is also essential for understanding their ecological roles and environmental significance, as plant, animal, and microbial indicators which exhibit unique responses to environmental stressors (Fig. 1).

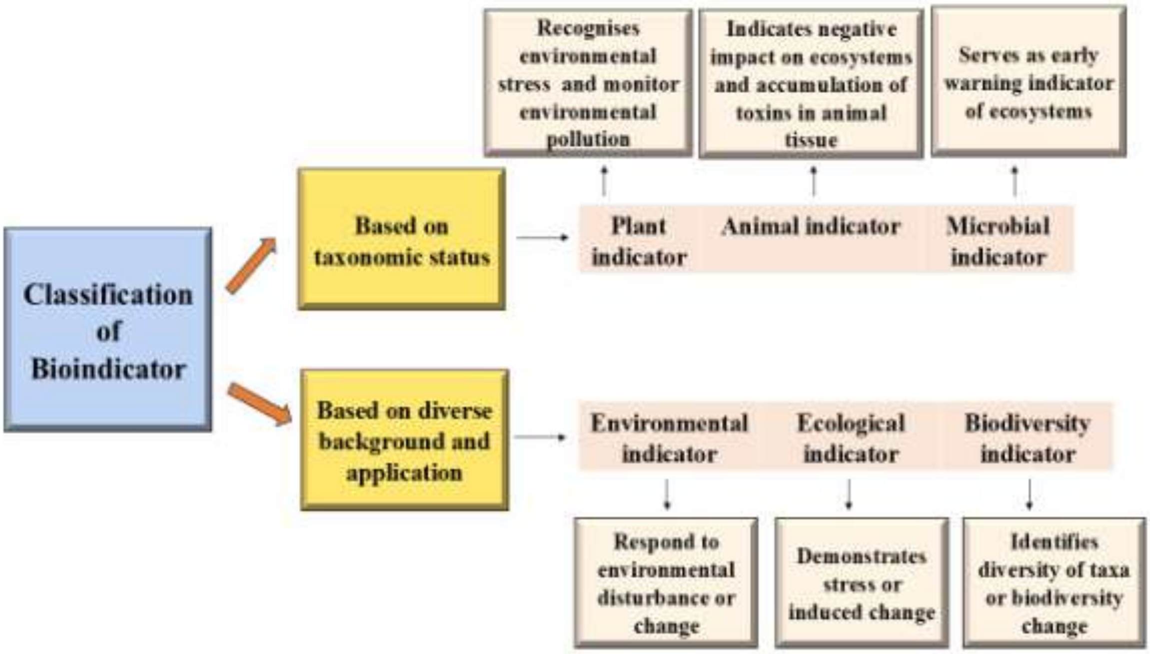

Fig 1: Classification of bioindicators (Chowdhury et al., 2023)[73]

Environmental indicators

Environmental indicators play a crucial role in detecting changes in the environment, facilitating the detection and quantification of these changes. The key characteristic of environmental indicators is their ability to respond predictably to environmental changes.

Ecological indicator

Indicator species or group of species can demonstrate the impact of stressors on ecosystems. These serve as a valuable tool for assessing the impact of stressors on ecosystems and tracking long-term changes, including habitat alteration, fragmentation, and climate changes.

Biodiversity indicator

A biodiversity indicator is a group of taxa or functional group that reflects the diversity of other taxa in a habitat. Biodiversity indicators are characterized by their ability to reflect the diversity of other taxa in a habitat, including metrics such as species richness, endemism, and functional group diversity.

Plant indicator

Plants are highly sensitive to environmental stress, making them useful for recognizing and predicting pollution. The impact of industrialization and urbanization on water contamination and pollution highlights the need for effective plant-based monitoring strategies[9][10]. Alterations in phytoplankton species composition, including changes in the abundance of Euglena clastica, Phacus tortus and Trachelon anas can be used as an indicator of marine ecosystem pollution[11].The presence or absence of lichens in forests serves as a reliable bioindicator of environmental stress, responding to changes in pollutant levels, including sulfur dioxide, sulfur and nitrogen pollutants [12].Cyanophyta, a biological indicator of planktonic activity, exhibits rapid eutrophication of aquatic habitats through the production of bloom patterns[13]. Furthermore, auto-fluorescence analysis of secretory cells in vegetative tissues or microspores offers a suitable method for monitoring ozone (O_3) levels and detecting early signs of damage caused by stress factors[14].

Animal indicators

Variations in animal populations can be employed as a bioindicator of ecosystem health, providing insights into the impacts of pollution on population dynamics**.**Changes in population density result from the complex interplay between populations and food sources. This relationship is mediated by various environmental factors, including pollution [15][11].Bioaccumulation of toxins in animal tissues can be effectively monitored using animal indicators, which provide a sensitive measure of environmental pollution[5].The use of zooplanktons, including Alona guttata, Mesocyclops edax, Cyclops and Aheyella as zone-based indicators of pollution enables the assessment of water quality, eutrophication, and contaminated water, providing a valuable tool for environmental monitoring[11][16]. Amphibians, specifically anurans, exhibit a high degree of sensitivity to environmental pollutants, making them an effective biological indicator of contaminant accumulation in ecosystems[17].Benthic macroinvertebrates play a critical role in indicating watershed health, as their ecological characteristics such as bottom-dwelling habits, multi-year lifespan, restricted mobility, and ability to integrate ecological conditions, make them sensitive to changes in environmental conditions, such as water quality and habitat degradation[18][5]. Invertebrates, including insects, serve as reliable bioindicators, providing valuable insights into ecosystem health and environmental stress.The application of insect-based bioindicators facilitates the assessment of environmental stress and ecosystem health, highlighting the need for conservation and management strategies to protect invertebrate communities and maintain ecosystem services (Fig. 2).

Microbial indicator

Microorganisms are widely employed as bioindicators of ecosystem health due to their abundance, ease of sampling, and rapid response to environmental stressors, and the induction of stress proteins in these organisms upon exposure to contaminants such as cadmium and benzene provides a sensitive biomarker for detecting ecosystem pollution and monitoring environmental health[5].Certain bacterial orders, including Opitulales, Chitinophagales, Cytophagales, and Saccharimonadales, have been identified as potential bioindicators of phosphorus-rich or nutrient-enriched [19].The use of bioluminescent bacteria as microbial indicators offers a valuable tool for monitoring water quality, as changes in bacterial light emission can indicate the presence of toxins and other environmental pollutants[20][21][22].The bacterium Vogesella indigofera serves as a bioindicator of heavy metal pollution, particularly hexavalent chromium, through its pigment production. In unpolluted conditions, the bacterium produces blue pigmentation, while chromium exposure blocks pigment production, providing a visual indicator of metal pollution[20][11][23].Soil microbial biomass is closely tied to soil organic carbon. Metrics like ratios of microbial biomass carbon to organic carbon and microbial metabolic quotient indicate soil carbon use efficiency, while soil enzyme activities correlate with microbial biomass carbon and nitrogen, making microbial characteristics useful bio-indicators of soil health [24].

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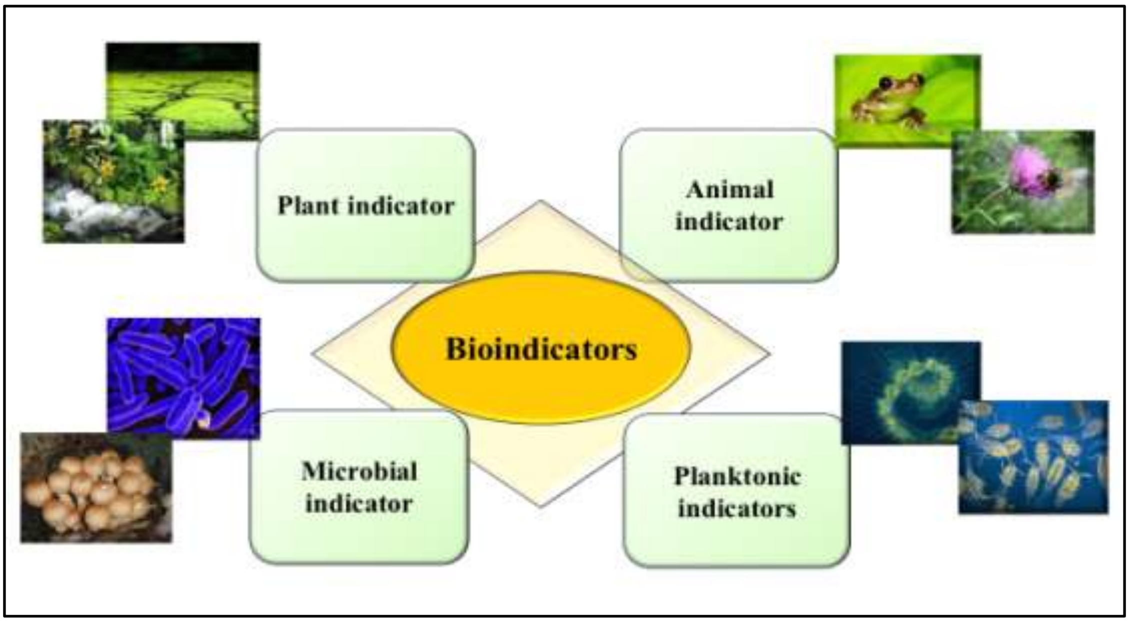

Fig 2: Types of bioindicators

Characteristics of bioindicators

The selection and application of bioindicators pose significant challenges due to their complexity and specificity. The selection of indicators mainly depends on the investigator's goal, such as assessing biological diversity, habitat destruction, climate change and pollution. A suitable indicator must meet various conditions, which vary according to the specific research objective[25].Ideal bioindicators possess specific characteristics, including well-established taxonomy, ecology, widespread geographic distribution, habitat specialization and sensitivity to environmental changes. They should also be cost-effective to survey, independent of sample size and responsive to anthropogenic stressors while distinguishing between natural and human-induced trends [26].Since the selection and application of bioindicators is a complex process, based on a comprehensive review of domestic and international research on bioindicator selection eleven selection standards have been established [25].

i. Species (or species groups) with clear classification and ecology
ii. Species (or species groups), those are distributed in a geographically widespread area.
iii. Species (or species groups), those show clear habitat characteristics
iv. Species (or species groups), those can provide early warning for a change
v. Species (or species groups), those can benefit promptly and economically from the investigation
vi. Species (or species groups), those are not adversely affected by the size of individual groups and have numerous independent individual groups
vii. Species (or species groups), those are thought to represent the response of other species.
viii. Species (or species groups), those are representative of the ecology change caused by the pressure of human influence
ix. Species (or species groups) for which research on climate change have been done
x. Species (or species groups), those are easy to observe, appear for a long time and form a large group of individuals
xi. Species (or species groups), those are significant in terms of culture, economy, and society.

Insects as bioindicators

Growing environmental concerns have fuelled the need for reliable bioindicators. Insects represent a substantial component of terrestrial species richness and biomass, fulfilling vital roles in ecosystem processes. Insects, in particular, offer a promising tool for evaluating environmental sustainability due to their sensitivity to ecological changes[8].Key characteristics of insect groups suitable for use as environmental bioindicators are mentioned below as given by [1]

- High species richness and diversity: The class Insecta is characterized by extraordinary species richness and diversity, comprising approximately 80% of the global animal species

- Easy handling: Majority of insect species exhibit ease of handling, facilitating capture and transportation, with exceptions among toxic species that require specialized handling protocols
- Ecological fidelity: Many insects are sensitive to environmental factors, making them reliable indicators of specific habitats
- Sensitivity to environmental changes: Insects exhibit high sensitivity to environmental changes, responding to subtle shifts in abiotic factors, which enables the identification of correlated demographic and behavioural variables
- Measurable responses: The quantifiable nature of insect responses to environmental changes enables the objective assessment of environmental degradation and its severity

Bioindicator insect groups

EPT taxa as bioindicator

Species within the orders Ephemeroptera, Plecoptera, and Trichoptera generally known as EPT taxa serve as sensitive indicators of aquatic ecosystem health, are widely recognized as bioindicators of good water quality. These aquatic insects thrive only in clean, cool, and well-oxygenated streams, making them sensitive indicators of water quality[27].

Odonata

These aquatic insects are top indicators of ecosystem health, quickly reacting to heavy metal buildup in water and riparian systems. Dragonflies are highly sensitive to habitat changes, especially in lakes and flooded areas [28]. The presence of dragonflies in a water body indicates a lack of synthetic pollution, suggesting a healthy ecosystem [29].

Lepidoptera

Butterflies are considered to be a reliable indicator species, providing insight into forest ecosystem condition through changes in their population dynamics, which can signal alterations in environmental quality and the presence or abundance of sympatric species [30]. Butterflies have been widely employed as bioindicators of heavy metal and environmental pollution, particularly in areas proximal to industrial sites and within metropolitan regions[1]. A study conducted in the Gir forest revealed, Danaidae and Nymphalidae butterflies were most abundant, while Hesperiidae was least dominant and also butterfly diversity was higher in disturbed forests, making them good indicators of climate change [31]. Butterflies are sensitive to temperature changes, affecting their life cycles, making them ideal for studying climate change impacts. Research has shown that certain moth families and subfamilies, such as Arctiinae and Heliothinae, exhibit positive responses to disturbances, whereas others, including Ennominae and Geometrinae, display negative responses [6]. Moths are also used to track vegetation recovery after environmental disturbances, serving as bioindicators of ecosystem health[7].

Diptera

The Order Diptera comprises a diverse assemblage of species, and its utility as a bioindicator is somewhat limited due to limited ecological knowledge of many fly species[1]. Chironomids are excellent bioindicators of spring water quality due to their abundance and diversity. They are also useful for monitoring surface water and groundwater quality, as their larvae are affected by sediment pollution. Antennal deformities can detect toxic environmental contaminants early [32]. Trace-metal contamination also causes recognizable genetic changes, making them reliable markers of genotoxicity[33].

Syrphidae flies are good bioindicators due to their wide distribution, well-known taxonomy, and varied larval environmental requirements. Changes in landscaping diversity, particularly reductions, significantly impact these insects [34]. They respond differently to various forest types, making them useful for comparing biodiversity [35]. Locally, they indicate habitat complexity, with species richness linked to vegetation structure.

Hymenoptera

Ants serve as valuable bioindicators of soil quality and play a crucial role in the rehabilitation of degraded and reforested areas)[36]. Due to their high sensitivity to human disturbance, ants can be employed as environmental indicators across diverse ecosystems [37][38]. These has been established as a sensitive and reliable bioindicator taxon for assessing various types of pollution, including soil contamination by heavy metals [39][40], aerial phthalate pollution[41], and land rehabilitation efforts [40]. Ants respond to land use changes in various ways, reflecting soil conditions, management practices, and cropping systems[42]. As ecological engineers, ants improve soil aeration, drainage, and nutrient availabilitysupporting sustainable agriculture [43].

Bees hold a pivotal position in biodiversity networks and ecosystems, exhibiting remarkable characteristics that render them exemplary bioindicators[44]. Honey bees are excellent bioindicators due to their ability to accumulate contaminants, inhabit varied habitats and cover large areas. Their mobility and sensitivity to environmental changes make them ideal for monitoring ecosystem health. Honey bees indicate environmental chemical disruption through two signals: mortality, often due to pesticide residues and contaminants like pesticides, heavy metals, and radionuclides detected in their bodies or hive products[45].

Parasitic wasps have complex, specialized habitat and recently, they have been used as bioindicators for woodland habitats[46]. Parasitoid assemblages are shaped by forest type and deadwood features, emphasizing the need to conserve diverse deadwood habitats. Parasitic wasps are complex and specialized due to their high trophic position, intricate biologyand restricted host ranges[47].

Coleoptera

Coleopterans, especially ground beetles (Carabidae), are useful bioindicators for environmental monitoring. They help assess environmental pollutants and forest management impacts[48]. Insects, especially Coleoptera, impact the distribution of toxic elements in the biosphere due to their role in food chains and metal transport. They serve as effective bioindicators for environmental monitoring and play a vital role in maintaining soil quality and ecosystem balance. Carabid beetles are sensitive to environmental changes, responding quickly to habitat fragmentation, grazing, fertilization and forest cutting. Temperature, humidity, vegetation and forest patch size all impact their populations [49].

Isoptera

Termites are common insects that indicate soil fertility and contribute to ecological processes like nitrogen fixation, soil transportation, and nutrient movement. They also play a key role in nutrient recycling and soil material transport. Termites indicate soil ecosystem services like fertility, hydrologyand biodiversity [50]. They also accumulate heavy metals, including Ca, Mg, Al, Fe, Zn, Cu, Mn, Be, Ba, Pb, Cr, V, Ni, and Cd[51].

Hemiptera

Species within the order Hemiptera, comprising various families such as Nepidae (water scorpions), Corixidae (water boatmen), and Gerridae (water striders), among others, have been identified as valuable bioindicators for evaluating water quality parameters [52].

Collembola

Springtails are sensitive soil arthropods that indicate changes in soil properties and human impacts. Their decline is linked to soil water acidity caused by organic pollutants, pesticides, and heavy metals[53]. Research conducted by Hasegawa et al. (2006)[54] investigated the community dynamics of Collembola during deciduous forest regeneration in Japan, providing insights into the ecological processes governing these ecosystems and concluded that collembolan abundance and richness recovered within 4 years after clear-cutting, but species composition of fungal and sucking feeders took longer to recover.

Insects as bioindicators of pollution

Aquatic Insects as Water Pollution Indicator

Aquatic macroinvertebrates are key to lotic food webs and sensitive to environmental changes, with different species showing varying levels of sensitivity. Aquatic organisms' tolerance to heavy metals is linked to metallothioneins, proteins that detoxify metals. Measuring metallothionein (MT) levels indicates an organism's metal tolerance and helps identify toxic agents causing environmental stress [1]. A range of indices, including Hilsenhoff's Biotic Index (HBI), Invertebrate Community Index (ICI), Biological Monitoring Working Party Score (BMWP), Macroinvertebrate Water Quality Index (MWQI), Average Score Per Taxon (ASPT), Percent Model Affinity (PMA), and EPT Richness Index have been employed to assess water quality based on specific criteria. Water quality degradation was observed in the Koratty River, Kerala affecting aquatic macroinvertebrates. Water quality decreased from upstream to downstream, with FBI values increasing accordingly. Both water quality index and family biotic index showed similar declines in water quality, confirming the Family Biotic Index as a suitable tool for monitoring stream water quality in the region[55]. A greater distribution and increase in species richness

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typically indicate better water quality, as a diverse range of species is often associated with healthier aquatic ecosystems [56].

Table 1. Benthic Macroinvertebrate Water Quality Bio-indicators

Sensitive:Good water quality	**Tolerant: fair water quality**	**Very tolerant: poor water quality**
Caddies fly	Alder fly larva	Black fly larva
Water penny	Water snipe fly larva	Leeches
May fly	Crane fly larva	Midge larva
Stone fly	Dragon fly naiads	Pouch snail

Terrestrial Pollution

Terrestrial insects are good bioindicators of environmental changes. Soil invertebrates indicate soil fertility and pollution. Excessive acidic or alkaline content, fertilizers, or industrial waste can kill insects and prevent them from laying eggs in polluted areas[57]. Metal concentrations in soil and ground beetles (Blaps polycresta) from a polluted site in Alexandria had significantly higher cadmium (Cd) levels than those from a reference site exceeding standard levels and also insects from polluted site had shorter body lengths and smaller, deformed gonads compared to those from a reference site [58]. Chandran et al. (2018)[59] studied metal accumulation in ants and soil in Chennai, Tamil Nadu. Ants from polluted areas had higher metal concentrations than those from unpolluted areas. Metal levels in ants correlated with soil metal content, with zinc and cadmium was found higher levels in ants. Heavy metal concentrations were investigated in predatory insects near a steel factory and control sites. The study analyzed waterstriders, dragonfly larvae, antlion larvae and antsrevealing higher metal concentrations near the factory, with the exception of waterstriders, which exhibited higher cadmium levels in control areas. These findings confirm the potential of these insects as indicators of heavy metal pollution [60].

Air pollution

Air pollution constitutes a formidable threat to the diversity of insect populations in urban environments, primarily attributable to acidification and nitrogen deposition. The specific pollutants responsible for this phenomenon include nitrogen dioxide, ozone, sulfur trioxide, volatile organic compounds, and particulate matter. The increased concentrations of O_3 and NO_2 pollutants were found to have a detrimental impact on urban butterfly diversity, resulting in a decline in butterfly families in Arroceros Park and Manila Zoo and Botanical Garden. This decrease in biodiversity serves as an indicator of poor air quality and highlights the need for conservation efforts to mitigate the effects of pollution on urban ecosystems[61]. Skorbiłowicz et al. (2020)[62] studied the impact of pollution on metal content in honeybees in Bialystok, Poland. They found Cu, Cr, Zn, Mn, and Fe in all bee samples, mainly from motorization, industry, and municipal activities. Metal contents were highest in summer, when bees are most active. Industrial chemicals harm ecosystems and can lead to biomagnification, where toxins accumulate in the food chain. The peppered moth's adaptation to industrial pollution is a classic example of this phenomenon. The decline of melanic moths (Biston betularia) at Caldy Common, England, and the George Reserve, Michigan coincided with improved air quality due to reduced sulfur dioxide and particulate matter emissions following the Clean Air Act [63].

Light and Sound Pollution

Insects are sensitive to light's periodicity, polarization, intensity, source, and wavelength[64]. Nocturnal insects have highly sensitive visual systems, with some having superposition compound eyes that s enables nocturnal insects to perform visual tasks with comparable precision and accuracy to diurnal insects, even in low-light conditions [65]. Light pollution can harm insects, affecting agricultural production. Artificial light at night disrupts insect communities and predator-prey interactions, altering the balance of agroecosystems. Foster et al. (2021)[66] studied dung beetles' orientation precision in Johannesburg, South Africa, under different sky conditions. Beetles performed better at a light-polluted site on overcast and starlit nights. On moonlit nights, there was no difference. The study suggests that light pollution led beetles to use artificial lights as

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orientation cues. Excessive night time light affects firefly (Photinus sp.) activity and mating attraction. As light intensity decreases, firefly populations increase, demonstrating the negative effects of artificial light on firefly occurrence[67].

Research has also shown that anthropogenic noise affects arthropod behavior and communication. Cicadas increase their call frequency with noise exposure[68]. Additionally, traffic noise disrupts female field crickets' ability to respond to male calls[69]. Increased background noise decreased the abundance of certain insect families, while compressor noise negatively impacted others [70].

Pesticide pollution

The use of honey bees for monitoring pesticides, a technique our group has employed since the 1980s, is a crucial method for assessing bee poisoning risks and evaluating environmental contamination caused by plant protection product. The monitoring paradigm comprising dual-beehive stations to investigate apiary-based mortality rates. Facilitated the identification of spatial and temporal patterns of bee poisoning riskas well as the detection of commonly used pesticides, including those prohibited by regulatory agencies[71]. Henry et al. (2012) [72]studied the impact of thiamethoxam on honey bees in Avignon, France. Tagged bees were tracked using RFID technologyrevealing that 10.2-31.6 per cent of exposed bees failed to return to their colony.

Benefits and Disadvantages of Bioindicators

Insects are characterized by their ubiquity in terrestrial and freshwater ecosystems, where they occupy a wide range of ecological niches in high abundance. Their relatively small size and short life cycles render them suitable for laboratory-based experimentation, which can be integrated with field monitoring studies. The maintenance of laboratory colonies of insects is also resource-efficient compared to larger animals. Arthropods are frequently employed as bioindicators due to the ease of collection using pitfall traps, which typically yield large sample sizes amenable to statistical analysis**.**

The utilization of bioindicators in environmental monitoring is widespread, driven by legislative mandates and international agreements. Nevertheless, their application is constrained by several factors. The sensitivity of bioindicators to environmental stressors can be compromised by natural variability, particularly in heterogeneous environments. Additionally, populations of indicator species can be influenced by extrinsic factors, including disease, parasitism, competition, and predation, which can confound the interpretation of monitoring data and obscure the causal mechanisms underlying environmental change. hey may not work well at all scales, and one species can't represent an entire ecosystem. Bioindicators also have unique needs that may not match other species. Relying on them can oversimplify complex ecosystems. Furthermore, insect species often respond to multiple environmental factors, making it challenging to identify the primary cause of observed changes. Different developmental stages may exhibit varying sensitivities to the monitored factor, and seasonal inactivation of species can also impact interpretation.

Notwithstanding their limitations, bioindicators provide substantial advantages in ecosystem assessment and management. They facilitate the evaluation of ecosystem health across multiple spatial and temporal scales, integrating biomarkers, abiotic factors, and chemical indicators. By providing critical insights into ecosystem function and resilience, bioindicators inform evidence-based sustainable practices, enabling proactive mitigation of anthropogenic disturbances and promoting ecosystem conservation.

II. CONCLUSION

In conclusion, the class Insecta possesses all the attributes of an ideal bioindicator, making it a crucial component of environmental monitoring. Insects serve as sensitive indicators of changes in soil, air, and water quality, reflecting these changes in their physiological characteristics and abundance. While selecting and recognizing specific indicator species can be challenging, the benefits of using insects as bioindicators far outweigh the difficulties. As we move forward, insects will play a vital role in detecting pollution and informing strategies to prevent habitat loss and reduce pollution**.**

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