Plant Bio-indicators of Air, Soil, and Water pollution: A Critical Review

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Abstract

Environmental pollution caused by urbanization, agricultural and industrialization poses significant threats to ecosystem health. The plants serve as effective bioindicators, providing a valuable insight into the type, intensity and distribution of pollutants across diverse habitats. This review synthesizes research from 2020 to 2025 on vascular plants, bryophytes, lichens and mosses as bioindicators of air, water and soil pollution. Each species demonstrating distinct morphological, physiological, biochemical, or genotoxic responses. Mechanisms such as phenolic accumulation, chlorophyll reduction, heavy metal bioaccumulation and micronucleus formation shows their diagnostic potential. Sensitive species such as lichens (*Plantago coronopus*) provide early warning signals, while tolerant hyperaccumulators species such as *Nuphar lutea, Alcea rosea* shows phytoremediation. The comparative studies reveals that the deciduous plants respond more rapidly to pollution than conifers. Further the scope of plant-based monitoring system enhanced by emerging approaches, including biosensors, electrochemical assays and remote sensing. Overall, the traditional plant bioindicators with modern analytical tools provides a cost-effective, reliable and sustainable strategy for environmental assessment and ecosystem protection.

Keywords: Bioindicators, genotoxic, bioaccumulation, biosensors, electrochemcal, pollution

Introduction

In past few decades, due to various human activities, the release of heavy metals and industrial pollutants has led to widespread environmental degradation, affecting the biosphere along with soil and water system (7). The total energy output from human-induced sources far exceeds that of natural sources (8,31). Industrial technologies often have undesirable consequences on the environment

due to gaseous emissions and untreated wastewater containing hazardous compounds. As a result, air pollution and soil contamination have emerged as major threats to plant survival in industrial vicinities and are recognized as potential causes of land degradation (15). Bioindicators play a crucial role in this context, as they can detect signals across multiple temporal and spatial scales, providing a consolidated assessment of ecosystem stresses. However, since bioindicators themselves are affected by these stresses, they are often species that show tolerance to certain stress factors (20). Understanding the physiological mechanisms such as the uptake and accumulation of pollutants in their tissues provide valuable insights into how these stresses impact bioindicators. This knowledge helps in designing effective bioindicators for future monitoring. An ideal bioindicator should exhibit a measurable response to environmental stress, and if the fate of pollutants within its body is known, its better understood (16). The toxic effects of metals on plants, for instance, may manifest as nutrient deficiencies, impaired water transport, reduced photosynthesis, or various morphological, physiological, and biochemical disturbance (13). Identifying plant traits that reliably indicate pollution requires specialized methodologies and the application of modern analytical tools (30,34). Despite this, relatively few studies have examined plant responses specifically to atmospheric air pollution. Research in this direction is increasing, with plants being used both to assess the impact of major anthropogenic systems on air quality and to monitor the environmental state of densely populated or industrialized regions (24,19).

Land, water and air are vital natural resources that transcend political boundaries and represent a shared concern for all of humanity (9). Within this context, specific plant species have proven to be valuable indicators of wetland ecosystem health. Beyond their bioindicator role, many of these plants are also recognized for their capacity to reduce pollutants through phytoremediation (a process in which contaminants are absorbed, accumulated and assimilated into plant tissues). This ability is driven by distinct physiological mechanisms, particularly the uptake of pollutants through roots and shoots (14). Building on existing literature, the present study aims to provide an overview of plant bioindicators in wetlands, focusing on their dual role in detecting and mitigating environmental stressors such as heavy metals, excess nutrients, urban runoff, wastewater, and water quality parameters associated with pollution (12). Aquatic plants not only provide critical insights into the condition of aquatic environments and serve as reliable indicators for biological monitoring of pollution, but they also play a vital role in removing contaminants such as dyes, heavy metals, hydrocarbons, pharmaceuticals, and pesticides from water (6). Many aquatic species are recognized as effective phytoremediators, capable of bioaccumulating toxins in their tissues and thereby contributing significantly to the reduction of aquatic pollution (4). Similarly, air pollution remains a major

global concern due to its detrimental impacts on both living organisms and non-living components of the environment. To classify an area as polluted, comprehensive environmental assessments, either bottom-up or top-down are essential (25). Air pollution is defined as the presence of harmful substances in the atmosphere, occurring in the form of solid particles, liquid droplets, or gases, all of which can pose serious risks to human health and ecological systems (22).

Materials and method

The present review was based on a comprehensive survey of published research papers from 2020 to 2025, focusing on the role of vascular plants, bryophytes, lichens, and mosses as bioindicator of environmental pollution (land, air and water) (11). The relevant peer-reviewed articles, books, and reports were collected using electronic databases includes Google Scholar. The following keywords and their combinations were used: Plant bioindicators, phytoremediation, air pollution, heavy metals, urban vegetation, lichen bioindicators, moss bioindicators, and industrial pollution (3,5,17,).

From the reviewed literature, more than 35 species were identified as environmental bioindicator (land, air and water). From these species, Woody ornamentals (*Bougainvillea glabra, Pinus sylvestris*, deciduous plants) act as effective indicators of urban and industrial air pollution, showing that morphological changes, fluctuating asymmetry, or biochemical responses eg., high phenolics, chlorophyll reduction. Leguminous grasses, Nuphar lutea, *Glycine max, Alcea rosea, and Plantago spp*., accumulate heavy metals and exhibit oxidative stress, altered photosynthetic efficiency, and tissue level accumulation, marking them as suitable accumulators and phytoremediators. Annual vs. perennial species from cement polluted zones (*Plantago coronopus vs. Artemisia herba-alba*) reveal differences in sensitivity and tolerance with annuals disappearing under stress and perennials adapting. Cryptogames remain highly sensitive indicators of gaseous pollutants (SO2, NOX, CO, dust) and heavy metals, reflecting changes in species richness, abundance, and morphology. Tradescantia pallida serve as a genotoxicity bioindicator detecting airborne mutagens through micronucleus formation. Wild or ruderal plants a halophyte (*Spartina alterrniflora, Carpobrotus acinaciformis*) demonstrate the potential to indicate and bioaccumulation.

Result and Discussion

Table-1: Plant Species that Serves as Bioindicators

Species	Pollutant	Habitat	Bioindicator Type	Response/ Mechanism	Reference
Bougainvillea glabra	Particulate matter, heavy metals in air and soil (Fe,Cu,Cd,Zn,Mn ,Pb,Ni,Cr,Co)	Industrial zones	Biochemical and Morphological Indicator	High level of pheonolics and flavonoids in leaves causes morphological changes	3
	Dust/Airborne particles	Industrial zones	Physiological Indicator	Dust deposition in the leaf surface reduces the chlorophyll synthesis	
	Air pollution (TSP, PM_{10}, NO, NO_2, NOx, SO_2, CO, CO2)	Industrial zones	Morphological Indicator	Leaf morphology, growth and productivity changes	
Leguminous grass	Zn,Cd,Cu,Fe,Ni, Mn	Agricultural soil	Accumulator/Phytoremediator	Heavy metal content from the stemming phase to flowering	17
Annual species (*Plantago coronopus, Plantago Arabica, Erodium retusa*)	Cement dust	Control site	Sensitive species indicator	Absent in polluted area	5
Perennial species (*Arthrocnemum armatus, Artemisia herba alba, Helianthemum kahiricum*)	Cement dust	Control site	Sensitive species indicator	Absent in pollutant area	
A.serratuloides, L.spartum, G.decander	Cement dust and Cr, Co, Zn, Pb	Polluted zones	Accumulator/Tolerant Indicator	For sink-trap species and offer their possible use in phytoremediation perspectives in a context of sustainable development	
Nuphar lutea leaves	Cd, Cr, Fe, Ni, Zn (Sediments)	Urban and Agricultural areas	Sediment pollution indicator	High metal levels in sediments, reflected in leaf concentration.	21

	Cr, Fe, K	Urban area	Metal specific indicator	High levels of metal contet in leaves indicate urban pollution	
	Cd	Agricultural areas	Metal specific indicator	Highest Cd conc. in leaves (fertilizers and pesticides)	
	Co, Mn, Ni, Pb, Zn	Forest areas	Low pollution reference	Low level of metal content in leaves indicate minimal human impact	
Wild and ruderal plants	PAHs, other contaminants	Urban and Rural	Accumulative, Comparative	Absorb pollutants from air, irrigation water and soil	32
Glycine max	La and Pb	Argicultural/ Urban, rainwater,soil	Biomarker, Electrochemical biosensor	High metal exposure causes oxidative stress, endocytosis, membrane damage and growth inhibition	33
	La+Pb	Industrial areas	Damage assessment indicator	Combined La+Pb stress at high levels is additive	
Vascular plants and Bryophytes	Industrial pollutants	Industrial zone	Phytoindicators, hyperaccumulators	Plants show structural plasticity and resistance to pollution	2
Pinus sylvestris L.	Air pollutant (urban, traffic, industrial)	All functional zones of Dubna	Coniferous bioindicator	Used to detect zoning of air quality, Shows stress due to air and possibly groundwater contamination	28
Deciduous woody and herbaceous plants	Air pollutant (traffic, industrial)	All functional zones of Dubna	Leaf fluctuating asymmetry	Sensitive to habitat changes caused by motor transport and industrial emissions	
Pinus sylvestris L. and deciduous spp.	Urban area pollutant	Urban landscape in Dubna	Comparative phytoindicator system	Deciduous plants reflect current pollution levels due to faster response and seasonal growth	

Lolium multiflorum var. ponto, Rumex acetosa L., Amaranthus retroflexus L., Plantago lanceolata L., Alcea rosea L., Lolium multiflorum L. var. Ponto	Cu, Zn, Cd, Pb	Urban soils, Poznan city	Reduction of chlorophyll content and relative water content, but in efficiency of photosynthesis parameters: net photosynthesis rate, intercellular CO2 concentration and stomatal conductance, we noted increased values, which proved the relatively good condition of the plants.	High level of Cd and Zn roots and leaves of *Alcea rosea* L.and Plantago *lanceolata* L. H_2O_2 level increases in roots and leaves of all species	10
Foliose - *Phaeophyscia orbicularis, Xanthoria parietina, Parmelia sulcata, Hypogymnia physodes* Crustose – *Lecanora conizaeoides* Fruticose – *Evernia prunastri, Ramalina farinacea*	Sulfur Dioxide, Nitrogen Dioxide, Dust, Carbon monoxide	Poltava and Kharkiv (central part, industrial areas, sleeping areas, park areas and green spaces)	Lichen indicator species	Shows strong correlation with pollution levels, Sensitive to air quality	26
Spartina alterniflora, Carpobrotus acinaciformis	Trace elements and Beach litter (mainly plastics)	Terrestrial	Bioaccumulation of metals	Demonstrating its utility in assessing beach pollution	27
Lichens	SO_2, NO_X, heavy metals	Trees, rocks, buildings	Natural bioindicator	Changes in species diversity, abundance, and morphology due to pollutant sensitivity	
Mosses	Heavy metals, nitrogen compounds	Moist, shaded surfaces	Natural bioindicator	Absorption and retention of airborne pollutants in tissue	

Tradescantia pallida	Airborne mutagens/genotoxins	Gardens, urban green spaces	Natural bioindicator	Micronucleus formation in plant cells as an indicator of genotoxicity	

By using Systematic Literature Review, research on plant bioindicators has expanded to cover a wide taxonomic range, including vascular plants, bryophytes, lichens, mosses, grasses, and woody trees. These taxa are distributed across diverse habitats includes industrial zone, agricultural fields, forest areas, urban landscapes, and coastal environments shows the broad applicability of plant bioindicators in different ecological contexts (Table-1).

Pollutant Specificity and Detection Mechanism

The reviewed studies reveal a strong focus on heavy metals (Cd, Pb, Zn, Cu, Ni, Mn, Fe, Cr, Co, La) and particulate matter, reflecting persistent industrial, vehicular, and agricultural contamination. Air pollutants such as SO2, NOX, and CO2 are also frequently monitored, particularly using lichens, mosses and trees as sensitive or accumulative indicators. The mechanisms of detection vary from:

- **Morphological and Physiological Indicator:** *Bougainvillea glabra* shows visible leaf morphological changes and reduced chlorophyll synthesis due to dust and airborne particles, while grasses and herbaceous plants indicate stress through altered growth and photosynthesis parameters (3).
- **Biochemical Indicators:** Elevated phenolic and flavonoid content in leaves, as observed in Bougainvillea, correlates with oxidative stress and pollution load (3).
- **Bioaccumulators and Hyperaccumulators:** Leguminous grasses, perennial halophytes and aquatic macrophytes accumulate heavy metals from soil or sediment, serving as quantitative pollution indicators (17).
- **Sensitive Species Indicators:** Absence of annual and perennial plant species in polluted zones demonstrates their role in ecological integrity assessment (5).
- **Molecular and Biomarker Approaches:** *Glycine max* and other species respond to metal exposure with cellular changes such as oxidative stress, membrane damage and genotoxicity, measurable through biomarker assays like the micronucleus test (Tradescantia pallid) (33,1).
- **Habitat-Specific Observations:** Industrial zones are repeatedly highlighted as hotspots for bioindicator application, with plants reflecting cumulative contamination from both airborne and soil-borne pollutants. Urban habitats show distinct pollution patterns, with *Pinus sylvestris* and deciduous species enabling spatial zoning of air quality (28).
- **Comparative Effectiveness:** Lichens and mosses remain natural bioindicators for gaseous pollutants and metal deposition due to their high

surface area and absence of cuticles, which allow direct absorption from the atmosphere. However, vascular plants offer advantages in pollutant-specific responses and potential for remediation (e.g., phytoremediation capacity of tolerant species). Notably, comparative studies in Dubna show deciduous plants respond more rapidly to pollution than conifers, making them valuable for current pollution assessments, whereas conifers integrate long-term trends (2,26,1).

- **Emerging Approaches:** Recent work includes the integration of remote sensing technologies and electrochemical biosensors for in situ pollutant detection (*Glycine max*). These technological integrations enhance spatial resolution and enable near real-time monitoring. Both the trace metals and microplastics, addressing the emerging issue of beach litter pollution (*Spartina alterniflora* and *Carpobrotus acinaciformis*) (33,27).

Conclusion

The reviewed studies from 2020-2025 clearly shows that the plants ranging from vascular species and grasses to bryophytes, lichens and mosses, serve as a reliable bioindicators of a wide spectrum of environmental pollutants. Specific species responses to morphological, physiological, biochemical, or genotoxic and that reflect the intensity and nature of contamination across diverse habitats such as industrial zones, agricultural fields, forests, and aquatic ecosystems. Sensitive species (Lichens*, Plantago coronopus*) provide early warnings, while tolerant and hyperaccumulator plants (*Nuphar lutea, Alcea rosea*) not only signal contamination but also contribute to phytoremediation.

Traditional bioindicators, when combined with modern approaches such as biosensor and UAV-based vegetation monitoring, it offers a reliable and cost-effective framework for large scale pollution. And the species responses with advanced monitoring tools can greatly increases the sustainable environment management and ecosystem protection.

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