

A Review of Plants as Bioindicators of Industrial Air Pollution

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ABSTRACT

Complex mixtures of gaseous pollutants, particulate matter, and potentially toxic elements are released from industrial activities and can change ecosystem functioning and human health. Conventional air-quality monitoring is still essential to quantify pollutant concentrations but is limited spatially and temporally by financial, technical, and infrastructural requirements, while plant-based biomonitoring integrates pollutant exposure over time and unveils biologically relevant responses. This review synthesizes evidence on the use of lichens, mosses, and vascular plants as bioindicators and biomonitors of industrial air pollution, focusing on plant responses to sulphur dioxide, nitrogen oxides, ozone, particulate matter, fluorides, and heavy metals, and on morphological, anatomical, physiological, biochemical, and bioaccumulation-based indicators. These include passive approaches that rely on the naturally occurring vegetation and active approaches that involve standardized exposure of selected organisms, and important assessment tools such as the Air Pollution Tolerance Index and lichen-based community indices. Recent studies show that plant biomonitoring can detect spatial pollution gradients, differentiate species-specific sensitivity and tolerance, and contribute to environmental monitoring in the vicinity of industrial facilities. Recent work shows that exposure to cement-dust can significantly alter the epidermal and stomatal morphology of plants, thus confirming the potential of locally available species for industrial biomonitoring. The review points out that plant bioindicators should be combined with instrumental monitoring instead of viewed as alternatives to it, and recommends more standardization, multi-seasonal sampling, chemical characterization of accumulated pollutants, and validation of indigenous tropical species to increase the reliability and policy relevance of plant-based monitoring, particularly in rapidly industrializing and resource-constrained regions.

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INTRODUCTION

While industrialization has led to economic growth, infrastructure development, and technological progress, it has also exacerbated the emissions of atmospheric contaminants from cement production, metallurgical processes, power generation, petroleum refining, manufacturing, combustion, mining, and other industrial activities that can emit particulate matter, sulphur dioxide (SO₂), nitrogen oxides (NO_x), ozone precursors, fluorides, volatile organic compounds, and potentially toxic elements, depending on the nature of the industrial process and fuel utilized (Lala *et al.*, 2023). Particulate matter, ozone, nitrogen dioxide, sulphur dioxide, and carbon monoxide are also identified as the major pollutants requiring evidence by the World Health Organization (WHO, 2021). The effects of industrial air pollution on ecological systems are not limited to direct effects on human populations atmospheric pollutants interact with vegetation on a continuous basis and may influence photosynthesis, stomatal functioning, water relations, membrane integrity, pigment concentration, oxidative balance, growth, reproduction, and community composition. This makes plants especially useful for documenting the biological impact of atmospheric contamination because individual plants are exposed to pollutants at specific

locations for long periods of time, and they integrate spatial and temporal variation in environmental conditions (Amaral *et al.*, 2025).

It is necessary to distinguish bioindication from biomonitoring: Bioindicators indicate environmental conditions through measurable biological responses (visible injury, changes in abundance, physiological performance, and anatomical features), whereas biomonitors can also provide quantitative or semi-quantitative information based on the accumulation of pollutants in tissues or standardized exposure-response relationships (Amaral *et al.*, 2025 Paoli *et al.*, 2023). In reality, the two concepts often overlap because the same plant can display symptoms of injury and accumulate atmospheric contaminants at the same time. The interest in plant-based approaches is partly due to the shortcomings of relying exclusively on conventional monitoring stations, which can provide important quantitative measurements, but can have limited spatial representation, require substantial technical capacity and financial investment for continuous monitoring, and cannot reveal cumulative exposure or the response of living organisms to complex pollutant mixtures. Amaral *et al.* (2025) in a comprehensive review of plant biomonitoring research highlighted the ability of plant-based methods to provide

spatial and temporal patterns of pollution and to supplement conventional monitoring, especially in areas where monitoring infrastructure is limited.

Plants as Bioindicators and Biomonitors of Atmospheric Pollution

Plants are a useful bioindicator of environmental quality, since they are usually sessile, continuously exposed to atmospheric conditions, and able to respond to pollutants through many biological pathways, such as direct deposition on the external surfaces, uptake through stomata, interaction with the cuticle, and incorporation into tissues after deposition and subsequent uptake (Amaral *et al.*, 2025). Responses can vary from subtle biochemical disturbances to obvious visible injury, and are influenced by pollutant concentration, exposure duration, climatic conditions, plant age, and inherent species tolerance. The advantage of plant biomonitoring is that it integrates exposure: whereas an instrumental measurement may reflect pollutant concentration at a specific point in time and space, plant tissues may accumulate evidence of exposure over days, weeks, or even months. This is especially important near industrial facilities where pollutant emissions may change based on production schedules, meteorological conditions, fuel use, and emission-control efficiency. The biological response also yields ecological information that concentration data alone cannot provide. Broadly, plant bioindicators can be classified into three functional groups: sensitive indicator species, tolerant species, and accumulator species. Sensitive species would develop a measurable biological response at relatively low levels of pollutant exposure and may therefore serve as early-warning indicators tolerant species may maintain growth and physiological activity under polluted conditions and could be useful for green-belt development or phytoprotection and accumulator species retain atmospheric contaminants in leaves, bark, lichens, or moss tissues and can be used for chemical characterization of deposition patterns. This is not an absolute classification because the response of a species can be dependent on the type of pollutant, concentration, climate, season, and local environmental conditions (Amaral *et al.*, 2025).

Major Industrial Pollutants and Plant Responses Gaseous Pollutants

Gaseous pollutants can enter leaves through stomata, where they can dissolve in the moist environment and then cause physiological or biochemical disruptions, with SO₂ and nitrogen-containing pollutants affecting cellular processes when exposure exceeds the detoxification ability of the plant and ozone acting as a strong oxidant that can cause oxidative stress and visible foliar injury. These are listed by the WHO (2021) as the major atmospheric pollutants for which air-quality guidelines are needed. Stomatal conductance, environmental conditions, and species-specific tolerance are factors that affect plant responses to gaseous pollution, and thus, changes in stomatal density, stomatal dimensions, pore condition, chlorophyll content, antioxidant activity, and visible leaf injury may serve as biological evidence of pollution stress however, similar symptoms may be caused by drought, nutrient limitation, temperature stress, pathogens, or other environmental factors, and therefore plant responses are most meaningful when used in conjunction with chemical or instrumental measurements and suitable control sites (Amaral *et al.*, 2025).

Particulate Matter and Industrial Dust

Industrial dust is also significant because particles can settle directly onto leaves, bark, lichens, and mosses, which can reduce light interception, block stomata, alter leaf-surface properties, and lead to the accumulation of associated metals or other toxic elements (Amaral *et al.*, 2025). An example of the association between particulate exposure and leaf anatomical traits was reported in a study of the Obajana cement-dust study (Kachi *et al.*, 2026). In *Azadirachta indica*, the number of epidermal cells and stomata, stomatal length, and stomatal breadth was reduced on the abaxial surface at the polluted site relative to the control site, and there were significant modifications in *Calotropis procera* with lower epidermal cell and stomatal counts and reduced stomatal breadth at the polluted site. Therefore, microscopic leaf traits can serve as measurable end points to assess industrial particulate stress. That same study also reported species-specific differences in response, with *C. procera* showing significant changes in several epidermal variables and *A. indica* showing a different pattern of response, an important principle in biomonitoring: species cannot simply be chosen based on abundance or availability they must be selected based on sensitivity, tolerance, morphology, leaf surface characteristics, and physiological behaviour in the relevant environmental conditions.

Heavy Metals and Potentially Toxic Elements

Atmospheric deposition of potentially toxic elements can occur from industrial emissions, combustion processes, mining, metal processing, and diesel-generator operation. They can be deposited on plant surfaces and accumulated in tissues, where their persistence and potential toxicity make plant-based accumulation studies particularly useful for identifying spatial gradients and potential emission sources. For example, Oladejo *et al.* (2025) studied bark and leaves of *Terminalia catappa* near diesel-generator facilities and found measurable accumulation of multiple toxic and heavy metals, with bark generally retaining pollution signals over longer periods and leaves providing more responsive evidence of relatively shorter-term exposure. Substantial particulate deposition was also observed by scanning electron microscopy, further supporting the utility of plant surfaces as passive collectors of airborne contaminants. Monitoring design must consider the complementary roles of bark and leaves bark may provide a longer-term record due to its persistent and structurally complex surface, whereas leaves may respond more rapidly to recent deposition and can also exhibit physiological or anatomical injury, depending on the tissue chosen for analysis (Oladejo *et al.*, 2025).

Fluorides and Mixed Industrial Emissions

There are some industrial processes that can result in fluoride emissions, such as metal-processing and manufacturing. Characteristic foliar injury on fluoride-sensitive plants can occur, with injury appearing around leaf margins and tips however, injury alone cannot be used for definitive source identification as several pollutants and non-pollution stressors can produce similar symptoms, and so symptom assessment is best used in conjunction with tissue analysis, pollutant measurements, meteorological information, and reference-site comparisons (Amaral *et al.*, 2025).

Lichens as Bioindicators of Industrial Air Pollution

Lichens have been used in atmospheric pollution studies for many years because their growth, community composition, physiological condition, and elemental composition can be highly responsive to air quality: their intimate association

with atmospheric sources of water and nutrients makes them particularly sensitive to changes in deposition and gaseous pollution, and lichen communities can indicate pollution gradients in terms of species richness, frequency, abundance, or the disappearance of sensitive forms. Lichen-based approaches may be particularly effective for large-scale spatial surveys because naturally occurring communities can be evaluated without repeated cultivation or transplantation, community-level methods can give evidence of long-term environmental conditions, and tissue analysis can be used to chemical assess accumulated elements however, interpretation must take into account the characteristics of the substrate, humidity, light exposure, microclimate, altitude, and other ecological variables that can affect the presence of lichens in their own right (Paoli *et al.*, 2023). Other studies have highlighted the importance of using lichen diversity and frequency in calculating indices of atmospheric condition and have identified the Index of Atmospheric Purity as one method for summarizing community responses (Świsłowski and Rajfur 2024). Index values may be useful to simplify comparisons among sites, but the ecological assumptions and species-specific sensitivity values employed in these indices must be suited to the region being studied. Developing locally validated lichen response systems is a significant challenge for tropical and industrial regions, and indices developed under temperate conditions cannot be automatically transferred to tropical ecosystems without testing due to differences in species composition and climatic controls therefore, future studies in Nigeria should focus on inventories of local lichen diversity, experimental sensitivity assessments, and calibration against instrumental pollutant measurements.

Mosses and Active Biomonitoring

This type of moss can be used as a biomonitors because they intercept and accumulate atmospheric deposition efficiently mosses are commonly used in active biomonitoring, where standardized moss material in mesh bags is placed at selected sites for a defined exposure period, and elemental concentrations can then be compared with background concentrations or summarized using accumulation factors (Świsłowski and Rajfur 2024). For example, Świsłowski and Rajfur (2024) showed that active moss biomonitoring was useful around an industrial facility, where *Pleurozium schreberi*, *Sphagnum fallax*, and *Dicranum polysetum* were exposed for three months, and industrially associated contamination was detected, with the accumulation of several elements differing significantly among moss species. Relative accumulation factors greater than one at specific sites suggested contamination related primarily to industrial activities, and wind direction affected the spatial pattern of accumulation (Świsłowski and Rajfur 2024). The moss-bag approach is advantageous in that it allows standard exposure, permits comparison between locations, and can be used where naturally occurring moss populations are not present or do not occur in suitable habitats, but it is also sensitive to exposure duration, species selection, sample preparation, hydration, seasonal conditions, and analytical procedures. Paoli *et al.* (2023) also noted the necessity of standardized preparation and exposure protocols when employing mosses and lichens as biomonitors. For industrial monitoring, active moss biomonitoring can be especially useful for mapping deposition around sources of emissions, where a network of exposure sites located along likely wind directions and at greater distances from an industrial facility can reveal gradients of deposition that may not be observable from a single fixed monitoring station.

Vascular Plants as Bioindicators and Biomonitors

Vascular plants are perhaps the most useful of biomonitoring organisms due to their ubiquity, ease of sampling, and their ability to express multiple complementary response variables (e.g., visible injury, leaf-surface deposition, chlorophyll concentration, relative water content, antioxidant responses, pH, anatomical modifications, stomatal characteristics, growth reduction, and tissue accumulation of pollutants). Global review by Amaral *et al.* (2025) emphasized the variety of plant species and methods used for air-pollution biomonitoring and the use of standardized grass cultures, especially *Lolium* species, which can improve the comparability between studies. Plant biomonitoring can also detect metals, nitrogen compounds, and organic pollutants and can identify spatial and temporal patterns of atmospheric contamination.

Lolium Multiflorum as a Standardized Biomonitor

The species that is used most widely in active biomonitoring is Italian ryegrass, *Lolium multiflorum*, because standardized cultivation and exposure can reduce some of the variability associated with comparing naturally occurring vegetation (Amaral *et al.* 2025). Standardized exposure can place plants of similar age and physiological condition at multiple locations, which can improve interpretation of spatial differences in pollutant accumulation, but the principal limitation is that standardized species may not always represent the sensitivity or exposure pathways of indigenous vegetation. Therefore, standardized biomonitors and local plant species are not mutually exclusive but should be considered complementary tools.

The Air Pollution Tolerance Index and Plant Sensitivity

A widely used framework for assessing the relative tolerance or sensitivity of vascular plants to atmospheric pollution is the Air Pollution Tolerance Index (APTI), which incorporates biochemical and physiological parameters such as leaf ascorbic acid concentration, total chlorophyll, leaf-extract pH, and relative water content. The conceptual value of APTI lies in the knowledge that pollution tolerance is a multifactorial process, and a composite index can provide a more holistic assessment than a single parameter such as chlorophyll concentration may reflect photosynthetic capacity and stress-related pigment loss, ascorbic acid contributes to antioxidant defence, relative water content reflects plant water status, and leaf pH may influence physiological responses. Although APTI cannot be directly related to ambient pollutant concentration, a high or low index indicates plant physiological characteristics at the time of sampling and may be affected by season, developmental stage, climate, soil conditions, and pollutant composition. Thus, APTI is most valuable when sampling and analytical procedures are standardized and used for comparative species classification.

Leaf Anatomical and Micromorphological Indicators

Another valuable category of biomonitoring endpoints is provided by microscopic leaf characteristics, such as stomatal density, stomatal index, stomatal dimensions, epidermal-cell characteristics, and the condition of stomatal pores, all of which may respond to environmental stress due to their direct relationship to gas exchange and leaf-surface functioning (Kachi *et al.* 2026). As these traits are directly related to gas exchange and leaf-surface functioning, they can provide biologically meaningful evidence of chronic exposure. The work of Kachi *et al.* (2026) is particularly relevant as they measured both adaxial and abaxial leaf surfaces of *A. indica*

and *C. procera* and reported significant differences between polluted and control locations for a number of epidermal and stomatal parameters, though the magnitude and direction of response differed between species and leaf surfaces. In addition, anatomical measurements such as the size of stomata and the appearance of the stomatal pores were recorded photomicrographically, including evidence of smaller stomata and stressed or clogged stomatal pores in leaves from the cement-dust-impacted area, providing evidence that anatomical measurements can support biochemical indices and data about pollutant accumulation. However, it is important to remember that light intensity, water availability, temperature, developmental conditions, and genetic variation can also affect stomatal characteristics, so robust biomonitoring studies require adequate replication, similar leaf age, reference sites, standardized microscopic procedures, and, where feasible, measurement of atmospheric pollutants at the same time.

Industrial Air Pollution and Locally Available Plant Indicators

There is a clear argument for greater plant biomonitoring in Nigeria as industrial activity is superimposed on other major atmospheric sources, including transportation, diesel generators, open combustion, and seasonal dust (Lala et al. 2023). The study by Kachi et al. (2026) on the Obajana case is particularly instructive, because changes in epidermal and stomatal traits were significantly correlated with cement-dust exposure, and *C. procera* was found to be more sensitive and *A. indica* more tolerant of particulate pollution, making *C. procera* a promising locally available bioindicator of industrial particulate pollution. Likewise, Oladejo et al. (2025) demonstrated that *T. catappa* bark and leaves can offer additional insight into heavy-metal deposition linked to diesel-generator emissions, which may be of significance in Nigeria, where the generation of power in rural areas can lead to localized atmospheric pollution. Combining bark for long-term accumulation and leaves for exposure assessment with high temporal resolution provides a model for multi-tissue biomonitoring.

CONCLUSION

Plant-based methods for assessing industrial air pollution include readily available, biologically relevant means to assess long-term changes in the quality of the atmosphere, such as the community composition and tissue accumulation of lichens, the use of mosses as sensitive passive or active collectors of atmospheric deposition, and the use of vascular

plants for visible, biochemical, anatomical, and bioaccumulation-based evidence of pollutant exposure. Standardized active biomonitoring, especially with *Lolium* species and moss-bag techniques, also has been shown to enhance spatial comparability between sites and should be considered a research and environmental-management priority in developing and validating indigenous plant species, especially in the vicinity of cement, mining, petroleum, power-generation, and manufacturing facilities.

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