

Medicinal Plants as Bio-Indicators of Urban–Industrial Air Pollution: Morphological, Anatomical, and Phytochemical Perspectives from Indian Industrial Regions

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Abstract:

Industrialization, urbanization, and vehicular emissions have depleted the environment in the case of air quality, markedly in major industrial zones in India. Conventional monitoring systems are rather precise but usually fail to take into account the cumulative biological effect of pollutants. Due to their sensitive physiology, metabolic diversity, and continuous exposure to atmospheric conditions, medicinal plants are considered reliable bio-indicators of air pollution. The consideration brought forth in this part is to make known the multi-faceted effect of urban–industrial air pollutants, especially the fine particulate matter ($PM_{2..5}$), sulfur dioxide (SO_2), and nitrogen oxides (NO_x), on the selected Indian medicinal plants from field conditions such as Azadirachta indica, Ocimum sanctum, and Ficus religiosa. In passing, the study analyzes morphological symptoms, physiological disruptions through stomatal occlusion, and the decreases in phytochemical constitution, with special note to the antioxidant inductions. The paper summarizes with the Air Pollution Tolerance Index (APTI) tolerant and sensitive species to be cultivated for conservation in a green belt and early warning systems. The proposed study is focused on the thresholding by these medicinal plants that are bestowed with pollution-ending protection potentials, whereas phytochemical pollution poses a challenge for the continuation of therapeutic and clinical science-based evidence on field trials and suggests an urgent call for regulatory and ecological interventions.

Keywords: Medicinal plants; Bio-indicators; Urban–industrial air pollution; Morphological and anatomical responses; Phytochemical alterations; Indian industrial regions

Introduction:

For the past two decades, the proverbial landscape of Indian development has been characterized by its hold over the extremely urban development and capitalism. In tandem with economic growth, all of these represent many forms of environmental degradation, mostly in the form of urban-industrial air pollution. The industrial sector's age emissions, coal-based energy generation, mining, and masses of vehicular traffic have directly resulted in enhanced concentrations of particulate matter ($PM_{2.5}$), sulphur dioxide (SO_2), nitrogen oxides (NOx), and other hazardous air pollutants across multiple primary industrial centers in India. National air quality notifications on several clusters have concluded their very frequent exceedance of

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prescribed National Ambient Air Quality Standards, especially during winter months, posing serious threats to ecological stability and public health. [1,2].

Plants, which are immobile and connected directly to the air, are highly sensitive to environmental background conditions. Living indicators of environmental traits, vegetation reflects integrated time effects of pollutants on air rather than short-term value concentrations and site-specific information here and now in an infectious pollution-monitoring experiment. Plants further demonstrate environment-wide changes via readily observed and measured growth, structure, and metabolic abnormalities on a longer-term basis and prove their worth in the identification of pollutant-induced stress through bio-monitoring [3]. Thus, bio-monitoring in plants has gradually become a very dependable, cost-effective, and ecologically suitable method to check out the air quality in urbanized industrial zones." The forest plants have a greater part and significance in the bio-indication. They are the basis of traditional medical systems like Ayurveda, Siddha, and Unani. The plants are widely used in the metabolic form of herbs, extracts, and nutraceuticals. Medicinal plants growing in polluted environments are immediately laden with atmospheric contaminants such as particulate matter and heavy metals, leading to changes in various aspects of plant physiology and phytochemistry. Such changes could therefore disadvantage the therapeutic /pharmaceutical usage of medicinal plants themselves or pose risks of toxicity from these principles in the pharmaceutical formulations to endanger the safety and quality of medicinal drugs [4,5]. Neem (Azadirachta indica) and holy basil (Ocimum sanctum) are thus the most used plants in Indian studies as sentinel and sensitive species. Being widespread in distribution, both have well-documented responses to pollution stress [6].

Plant morphology, which is likely to have been altered as a result of air pollution, represents one of the major early indicators. Visible symptoms, like chlorosis, necrosis, reduced leaf area, and premature leaf fall, are generally encountered in plants growing in industrial zones and high-traffic areas [7–9]. At the anatomical level, pollutions can be responsible for the alteration of micromorphological features such as the closure of stomata down to micron-particle clogging, changes in epidermal thickness, and increased trichome densities, all of which affect gas exchanges, transpiration, and photosynthetic mechanisms [10–15]. Such changes that relate to some form of structural injury and modification may also be seen in response to pollution hold signs of the adaptation of the biosphere to pollution.

Apart from mere structural effects, interconnections and interchanges can be found between plant physico-chemical and cellular biochemical processes, influencing the pollutant fate. Any pollutant-induced kind of oxidative injury leads to the synthesis of one or another secondary metabolite, like phenolic acids, flavonoids, antioxidants, to a certain extent, for the defense mechanism against stress [16–18]. The probable enhancement of chloride tolerance in the plant, resulting from these alterations in biochemical makeup, might also potentially change the level and content of major phytochemicals responsible for the medicinal efficacy of pomegranate. Heavy metals and gaseous pollutants interfere with essential oil biosynthesis and contaminate plant tissues, raising health concerns among consumers of medicinal plants [19–21].

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The current study aimed to determine the role of several Indian medicinal plants as bio-indicators in urban and industrial air pollution based on morphological, anatomical, and phytochemical investigations. The study focused on identifying pollution-tolerant and pollution-sensitive medicinal species that could be employed for the development of green belts and environmental surveillance in industrial areas, carrying out Air Pollution Tolerance Index ratings [22,23]. So, classifying and characterizing medicinal plants exposed to air pollution is precisely important not only to environmental assessment and urban ecological planning but also precisely to the safety, quality, and sustainability of Indian traditional medicinal plant resources in an industrializing economy.

Materials and Methods:

The present study was conducted in the selected urban and industrial areas of India, representing pollution load due to industrial activities and vehicular movement, with control areas serving as the rural villages with comparatively less pollution. The medicinal plants used in the study were Azadirachta indica, Ocimum sanctum, and Ficus religiosa, which commonly grow in both types of environments. Healthy and mature leaves were randomly collected during the corresponding seasons so as to minimize the impact of climate on the experiment. The ambient air-quality data, including the levels of $PM_{2.5}$, SO_2, and NO_x, were collated from nearby monitoring stations. For a better determination of pollution effects, some morphological parameters and such observations as leaf area, visible injury, growth indicators, etc., were noted in the field. Anatomical studies have been undertaken through light microscopy. They aimed to determine the stomatal structure, epidermal thickness, and particulate deposition. The phytochemical exposure included the estimation of total chlorophyll, ascorbic acid content, phenolic content, and essential oil yield, using the standard biochemical protocols. Other parameters that constitute APTI were derived from Relative Water Content and Leaf Extract pH. The gathered data were analyzed statistically, and their calculation means were compared to determine pollution-induced changes between the polluted and control sites.

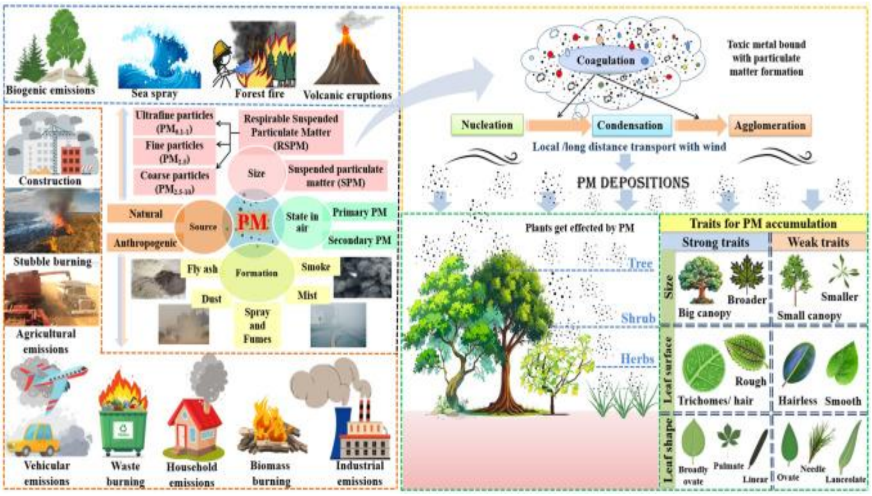
The Indian Environmental Context:

Air Quality Challenges in Industrial India

The state's recovery from 2020 to 2025 has thus been a challenging period for the industrial set-up in India, with a substantial surge in the manufacturing, energy, mineral resource exploration, including the propane and gas industry, and heavy vehicular traffic. While instrumental in propelling economic development on a large scale, such industrialization also substantially increased environmental stress, most notably in the form of air pollution. The Vapi-Ankleshwar chemical belt in Gujarat, the Singrauli coal-based power cluster, and the Mumbai-Pune-Nashik industrial corridor in Maharashtra are some of the most heavily polluted regions in the country.

The Central Pollution Control Board (CPCB) in its recent study found that the high winter and summer-time pollution levels of suspended particulate matter (SPM), $PM_{2.5}$, and gaseous pollutants like SO_2 and NO_x usually exceed the National Ambient Air Quality Standards (NAAQS). [1]. Within several industrial clusters, pollution levels can increase by a maximum of around 300%. This fact imposes a colossal threat to ecological integrity and public health [2].

Stress states following long-term and sustained doses of pollutants, in contrast to episodic pollution events, establish a chronic pollution status for urban vegetation. Industrial emissions, coal combustion residues, and vehicular exhausts introduce complex mixtures of particulates, heavy metals, and reactive gases into the atmosphere. Such pollutants perturb air chemistry and directly interfere with plant surfaces, tissues, and metabolic pathways. As such, vegetation in industrial areas becomes chronically stressed in many ways and can serve effectively as an integrative monitor for overall environmental quality.



Source: *https://doi.org/10.1016/j.stress.2024.100671*

The Concept of Bio-Indication

Plants are a safeguarding species for the biodiversity of the Earth. Plants protect the soil, provide oxygen, retain moisture, build shelter, and feed many life forms above the ground. The plants have been placed in every imaginable space, including squeezes between rocks and on steep inclines, following you at the market, around the garden, and even between hairpin bends, making you leisurely inland from the sea [3].

They sit at a genesis identified by medicinal plants within the bio-indication. Besides their ecological roles, these plants are harvested and consumed for therapy, which renders their contamination a direct public health liability. Changes in their morphological traits, internal anatomy, or phytochemical composition severely hit their medicinal value and safety [4]. The effects of pollutants on secondary metabolites may result in decreased therapeutic potential or toxic accumulation in plant tissues.

Plants shown in bio-assessment research, like Ocimum sanctum and Azadirachta indica, are conspicuous in their distribution, possess foliage throughout the year, and reveal a complete picture of their physiological reactions regarding environmental stress [5,6]. Their susceptibility to airborne pollutants makes them very well adapted to become early warning devices and tools to appraise comprehensive pollution analysis over a broad, urban–industrial landscape.

Morphological and Structural Responses:

Growth Retardation and Foliar Damage

The most evident and immediate effect of plants on air pollution is morphological alteration. Due to the incessant existence of dust toxic from industries, vehicular emissions, and acidic gases, there is the disturbance of cell elongation and the process of leaf development, resulting in several distinguishable symptoms such as chlorosis (yellowing of leaves), necrosis (localized tissue death), curling, and premature defoliation in the plants near industrial areas [7].

Studies conducted in 2024 and 2025 concluded that significant foliar damage was found in roadside and industrial-adjacent vegetations in Mumbai's industrial corridors. Cassia fistula, an important medicinal species, exhibited almost 40% lower leaf area compared to the specimens from control sites in rural conditions [8,9]. A decrease in leaf area is many a time an adaptive response intended to limit the available surface for pollutant deposition and, subsequently, to minimize the transportational uptake of a pollutant [10].

Slowing growth in medicinal plants can have effects that extend beyond essential plant health. Small biomass and leaf areas can lead to a decreased yield of plant parts used in various forms of traditional medicine. While scales have a somewhat inverse relationship with growth retardation, shorter leaves, and thinner stems (all of which are signs of slow growth), such a correlation could also lead to reduced availability of raw herbal material, thereby impacting ecological sustainability and the herbal pharmaceutical supply chain.

Anatomical Alterations and Stomatal Clogging

When leaves from polluted environments were examined under a microscope, serious anatomical modifications were observed. Yet, among some of the most documented observations, one must note the occurrence of stomatal clogging due to the deposition of fine particulate matter and carbonaceous residues from vehicular exhaust-all that can clog stomatal esophoria, thus impairing gas exchange, the process of photosynthesis, and transpiration [11].

Research along Delhi's industrial periphery revealed the existence of severe stomatal blockages in Ficus religiosa with considerable reduction in stomatal conductance and efficiency in transpiration [12,13]. These anatomical damages reduce the CO_2 uptake, leading to a retardation in photosynthetic productivity and subsequently depressing organic production, bringing about plant stress (physiological).

Adaptive types of structural changes have been noted for some medicinal species. However, a higher density of trichomes on plant surfaces is thought to serve as a defense mechanism that slows down or traps particulate matter before it can cause damage to sensitive epidermal tissues [14,15]. The increase in thickness of the cuticle and the alteration in the epidermal cell walls not only increase the resistance to the penetration of pollutants, but these anatomical features end up enervating the plant survival through impaired physiological efficiency and altered metabolite synthesis.

Phytochemical Transformations and Stress Markers:

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Oxidative Stress and Alteration of Secondary Metabolites

Air pollutants in urban–industrial environments bring about severe oxidative stress in plants by causing excessive Reactive Oxygen Species (ROSs), including the superoxide radical, hydrogen peroxide, and hydroxyl anions. Gases like $PM_{2.5}$, SO_2, and NO_x either kill oleic bodies in the atmosphere or stimulate an area within stomatal pores to induce constriction [16]. Persistent oxidative stress damages lipids, proteins, nucleic acids, and photosynthetic machinery, thereby threatening plant survival.

Medicinal plants, however, respond to stress by activating the defense system against antioxidants that include enzymatic antioxidants such as superoxide dismutase, catalase, and peroxidase, and nonenzymatic antioxidants such as phenolics, flavonoids, tannins, and ascorbic acid. A recent study carried out around coal-fired power plants and industrial clusters in central and western India has shown a significant increase in Total Phenol Content (TPC) and flavonoid concentration in A. indica growing in polluted environments. [17,18]. The last surrogates are producing more of the antioxidant defense in terms of chronic potential, but that may subvert an imbalance in natural plant chemicals inherent in the potent biological efficacy of the plant. Too much of certain metabolites might also increase antioxidant potential, but at the greater cost of destruction of the synergistic relations among the bioactives, on which Ayurvedic designs were heavily dependent. The biopurification effect, therefore, is a double-edged process: ecologically advantageous and pharmacologically indecisive.

Impact on Essential Oils and Bioactive Constituents

The valuable therapeutic potency of medicinal plants is closely related to secondary metabolites, including essential oils, alkaloids, glucosides, and terpenoids. The presence of industrial pollution and heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni) affects the biosynthetic pathways responsible for myriads of compounds produced by plants. Indeed, these pollutants of industrial origin can accumulate on the leaf surfaces and penetrate tissues [19].

Studies in 2025 showed that Ocimum sanctum grown in excessively contaminated air-rich conditions are reduced by almost 25% in the yield of essential oil compared to plants grown under less polluted conditions in rural places [20]. The leaf tissues generally used for herbal infusions and ext. showed an imperative rise in the concentration of the metal contents. [21]. These agents bind to the sulfhydryl groups present in proteins in order to inhibit various enzymatic activities, as well as alter the oil/floral composition.

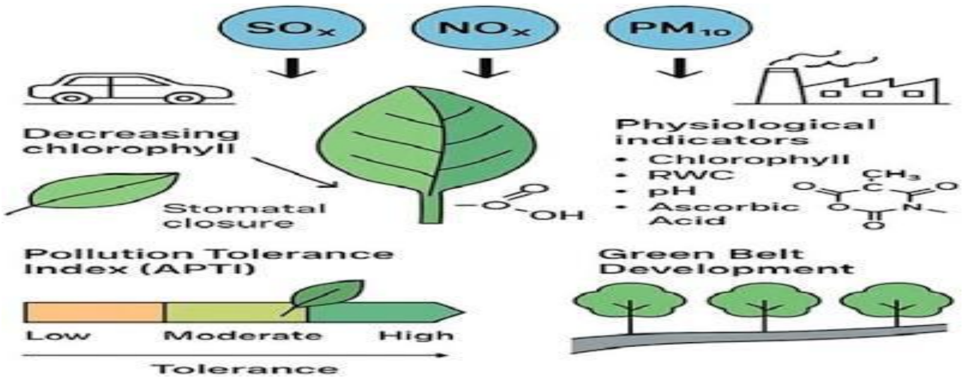
The pollution raises critical concerns regarding human health. As per the updated WHO Herbal Safety Guidelines, long-term ingestion of metal-contaminated plant products can lead to bioaccumulation and chronic toxicity [22]. Because of its economic viability and applications, methyl tert-butyl ether (MTBE) is associated with an environmental impact in developing countries.

The Air Pollution Tolerance Index (APTI)

Conceptual Framework of APTI

The Air Pollution Tolerance Index (APTI) is a commonly used quantitative method employed to assess the tolerance or sensitivity of plant species against pollution-stress. It pools four physiological and biochemical parameters: total chlorophyll content, ascorbic acid concentration, leaf extract pH, and relative water content. The composite index is an expression of the organism physiology Vis-a-Vis the pollution conditions. [23].

Plants having enormous APTI scores are considered tolerant and can be recommended for plantation in an industrial green belt, while those with a lower score are recognized as sensitive and act as early biological indicators. However, the APTI procedure has proved itself most significant in the arena of Indian environmental studies because of its simplicity, peculiarities, and practical implications in urban planning and ecological management [24].

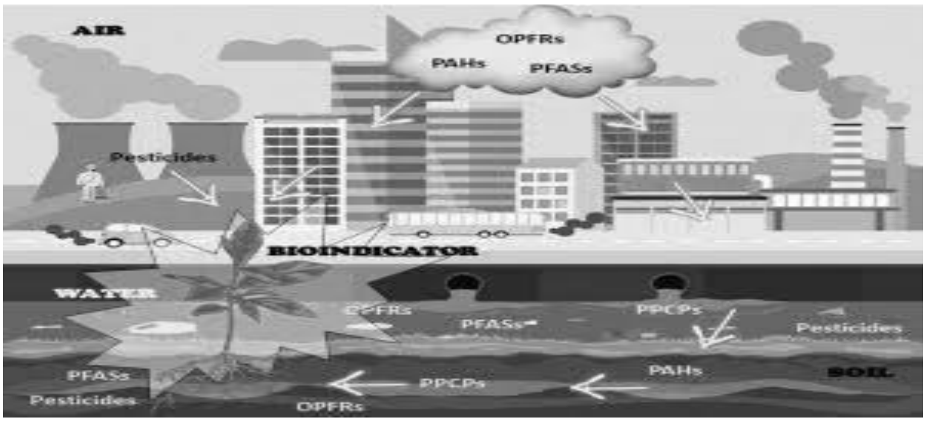


Tolerant and Sensitive Medicinal Species

Field indirect research carried out in industrial regions in India for two years, 2024 and 2025, has always been consistent in identifying Azadirachta indica and Ficus benghalensis as pollution-tolerant species. Whenever their APTI values are above 25, they are usually ascribed to be rich in ascorbic acid, having stable levels of chlorophyll and showing a strong ability to hold water [25,26]. Their robust physiological systems favor the plants to withstand oxidative stress and maintain metabolic functioning even when exposed to high loads of pollutants.

On the other hand, it is commonly found that Ocimum sanctum has frequently shown low APTI values, mostly less than 12, falling in the range of sensitive species [27]. Largely due to reactive oxygen species, the primary air pollutant in larger doses induces stress and distress to the airways. It has significant potential for airway infection in predisposed patients. A similar gas is a potent stimulus for the generation of free radicals.

As a countermeasure to CO fluctuation at the exposure point, body's effective antioxidants-registration of a mental perimeter. Anything that daunts pH paves the way for the etiopathology of chronic pulmonary disease and can lead to mortality.



Conclusion:

The idea that would have until now been given only as elaborative observation and would be important to integrate an ecological and pharmacological sort of a model. Morphological delays are seen through development like reduction of foliage area, anatomical, and histological, from being focused on elsewhere like, why not?-for instance, stomatal closure, to biochemo-physical in light of oxidative stress leading into antioxidant overproduction in Indian heavy industrial regions. Such are important medicinal herbs for both while maintaining fragile air qualities and attaining maximum front converting phytochemical and heavy metal loads, beyond human reasoning! Hamletian Sof that state: "To act and to be dastardly unsafe for any use for clergy"? Clatter bildernised the flooding mags of refinement, Multidrug, and Quality Control in Ayurvedic Antibiotics multiplied a million times an inch. Dissected soils of traditional "herbal pharmacy", that unbraided entwine for severe damage to public health, Ayurvedic pharmaceuticals, and fundamental recognition itself. Subsequent studies should further embank traditional assay plants, ranging in autumn with high-resolution molecular studies like metabolomics, air pollution assessments based on AI, and geospatial analysis of risk maps. Legal frameworks should set forth pollution-free cultivation zones for medicinal plants, suggesting reasonably consensual quality control on herbal raw materials. What should be achieved, only from an interdisciplinary and policy stance? In this regard is important to consider the efficacy of these plants with the benignity of the environment.

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