



Heavy Metal Accumulation and Its Effect on Phytochemical Constituents of Medicinal Plants Growing Near Thermal Power Stations

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Abstract

Thermal power stations, including other anthropogenic sources, release high levels of potentially toxic heavy metals, including Cadmium (Cd), Lead (Pb), Chromium (Cr), Nickel (Ni), Arsenic (As) and Mercury (Hg), into the environment via fly ash, water plumes, and wastewater effluents. Persistent metal deposition alters the actual properties and increases metal bioavailability, facilitating plants' uptake from the industrial peripheries. Medicinal plants collected from areas around thermal power stations have therefore taken up these metals to a greater level of toxicity than the permissible limit, giving rise to apprehensions regarding consumer safety. Contrastingly, an increasing body of evidence has pointed toward the impact of heavy metal stress on plant primary and secondary metabolism that leads to important changes in the quantity and quality of bioactive phytochemicals. E.g., phenolics, flavonoids, alkaloids, and terpenoids, thereby determining the therapeutic abilities they boast. The present review merges research works published between 2019 and 2025 on (i) heavy metal contamination in the soil and water bodies around thermal power plants, (ii) accumulating patterns in medicinal plants. (iii) mechanistic associations between metal-induced oxidative stress and the modulation of phytochemical pathways, and (iv) implications on pharmacological quality and human health. Field and experimental studies indicate that necessary antioxidant phenolic and flavonoid biosynthesis are often promoted by oxidative stress responses caused by heavy metals, thereby suppressing or modifying other metabolite classes according to metal type, concentration, species, and organ constraints. The review stresses the ongoing urgent need for systematic monitoring of heavy metals and phytochemicals in the medicinal plants collected around power plant complexes, stringent regulation of allowable limits for herbal commodities, and the integration of phytoremediation-based landscape management for lessening environmental and human health risks.

Keywords: Heavy Metals; Thermal Power Plant; Medicinal Plants; Phytochemicals; Phenolics; Flavonoids; Oxidative Stress; Bioaccumulation; Human Health Risk

Introduction:

Thermal power plants are important electricity generators in many developing and transitional countries, with coal- and lignite-based plants holding the greatest market share. However, several of these facilities have long histories of environmental pollution from point sources, producing significant amounts of particulate matter, sulfur oxides, nitrogen oxides and trace metals [1,2]. During combustion, the lithogenic material would concentrate the metals from burning together in coal during combustion. This led ash and bottom ash to loom unto slurry ponds or unlined landfills situated very near agricultural land and areas constitutively inhabited by humans [3]. It could be appropriate to consider the direct off-site impacts of disposal activities occurring on municipal solid waste landfill sites, which facilitate the spreading of contaminant load to off-local ecosystems.

A great number of investigations presented regarding heavy metal-affected altitudes of Pb, Cd, Cr, Ni, Zn, Cu, and Hg in lands around coal-based thermal power plants, surpassing regional background levels, and biological advisory threshold values [4–6]. Further studies of seasons and accumulation of metals have indicated that there are several influences, including different seasons, rainfall types, direction of winds, and ash disposal



practices; concentrations are generally higher over dry pre- and post-monsoon periods due to increased incorporation of fluvial-ash [7].

Many species are located in poor soils with a lesser capacity for growth as they grow in the close vicinity of big industries. Temperature inversions and meteorological conditions may induce the capture of sulfur that accelerates sulfur in the burnt fuel-air colloid. While the effect is mostly local, very rarely, it can directly cause porosity of neighboring ground surfaces [8]. Heavy metals accumulating in such plants not only bring immediate risks for human health, but they also impair plant physiological processes such as photosynthesis, respiration, and nutrient equilibrium [9]. Besides oxidative stress, membrane injury, and DNA instability, ROS boost the excessive production of heavy metals [10].

In order to counterbalance metal-triggered oxidative stress, plants plummet into a complex array of defense strategies backed by enzymatic antioxidants and low molecular weight secondary metabolites, such as phenolic acids, flavonoids, tannins, and alkaloids [11]. Phytochemicals are highly instrumental and the very embodiment of the medicinal potency of herbals and sometimes food, whereas exuding antioxidant, anti-inflammatory, anti-microbial, and, sometimes, anti-cancer activities. The weight of findings suggests that heavy metal stresses can significantly alter both levels as well as the profile of these metabolites, thus potentially altering pharmacological implications vis-à-vis safety [12,13].

Our understanding becomes fragmented as locality-honed information multiplies around thermal overburdening of metallics in Medicinals. The review at hand attempts to consolidate recent information offered on heavy metal contaminants around the site of plants, their accumulation within medicinal plants, how they metallize the plant from within, affect the phytochemical composition, and their impact on human health and regulations.

Materials and Methods:

The selected articles from January 2019 to December 2025, were subjected to a narrative-synthesis approach. The scientific databases were thoroughly scoured with ideal terms, employing features that include Web of Science, Scopus, PubMed, ScienceDirect, and Google Scholar. The (blended) keywords were: thermal power plant, heavy metals, fly ash, medicinal plants, heavy metal accumulation, phenolic compounds, metal stress, and antioxidant activity from contaminated plants.

Studies were included if they (i) concentration of heavy metals were openly reported in the fly ash, soil, plants, or waters that discharged in the nearby of thermal-powered or coal-fired generating plants, (ii) assessed heavy metal accumulation in medicinal plants, or (iii) from the experimentation on the breakdown of the levels of phytochemicals and antioxidant activity caused by metal stresses. Studies that focused on ill or non-metal pollutants were eliminated; however, priority was given to studies that had simultaneously studied the artificial load of metals along with phytochemical or biochemical standards.

For evaluations of metal load analyses, the relevant techniques employed mostly were atomic absorption, inductively coupled plasma optical emission spectrometry (ICP-OES), and inductively coupled plasma mass spectrometry (ICP-MS), while phytochemical parameters were assayed along with colorimetric systems (Folin-Ciocalteu, aluminium chloride) and chromatographic methods involving HPLC or LC-MS [14,15].

Heavy Metal Contamination Around Thermal Power Stations:

Sources and spatial distribution

As a result of the intense heat, volatile and semi-volatile metals such as cadmium (Cd), lead (Pb), chromium (Cr), nickel (Ni), zinc (Zn), manganese (Mn), and mercury (Hg) are concentrated in fly ash particles, which are mostly emitted from stacks during power generation [3,4]. Fly ash particles, because of their smooth surface and small size, are easily carried by wind over long distances, while bottom ash is trapped locally in ash



ponds and landfills, thereby contributing significantly to heavy metal contamination in terrestrial environments around it.

In many field tests, considerable portions of Pb, Cd, Cr, Ni, Zn, and Mn were detected in surface soils near thermal power plant sites, with particularly high concentrations documented in the areas near coal ash ponds, coal handling and unloading areas, and plant fences [5,6]. This is the case more often than not, along with a rather clear spatial gradient; the highest concentrations of whatever pollution are usually situated just miles from the emission sources in the down-gradient direction and decline with distance from the sources. These spatial patterns are closely associated with the deposition of metals from fly ash emissions in the atmosphere, with subsequent leaching from ash storage heaps. Soil properties like pH, organic matter content, and the nature of the clay largely determine the region's ability to retain and move around metals and can often augment the process of accumulation in the topsoil, where plant roots are very much active.

Inquisitiveness of coal-fired power plants in Turkey and Iran has brought forth all the more significance of very high pollution levels of Cr, Ni, and Hg using geoaccumulation indices, enrichment factors, and pollution load indices [4,6]. These could form a clear distinction between anthropogenic input and the natural geochemical environment and attribute the main contributors, i.e. primarily the power generation sector, to metal enrichment. Interestingly, another study that recorded similar observations was from an Indian coal-based thermal power plant, where the data of seasonal monitoring show high metal concentrations around the soil during the pre-monsoon and post-monsoon periods [7]. These seasons' dry conditions promote the increase in fly ash's atmospheric deposition, minimizing metal leaching, and hence more accumulation in the surface soils.

Impacts on water resources

Aside from the soil pollution, thermal power stations pose substantial risks to the surrounding surface water and groundwater systems. Leachates generated by ash ponds, unlined disposal sites, and contaminated soils allow the transport of heavy metals into adjacent rivers, canals, and aquifers [2,16]. Basically, human beings (communities) exploit water to fulfill their lives, like drinking water, water for domestic use, and livestock, or for their farms.

The concentration of aluminium (Al), magnesium (Mg), mercury (Hg), and lead (Pb) in the water from surface flows and wells near thermal power plants suggests modeling biomonitoring map [16,17]. Protracted consumption of contaminated water presents chronic metal exposure, possible to generate neurological disorders, kidney dysfunction, cardiovascular ailments and developmental effects, for instance, in the fetal and elderly age. Moreover, the reuse of contaminated water for irrigation can exacerbate soil pollution and increase metal uptake into the roots of crops and medicinal plants, thus amassing ecological and food chain implications. These findings that have been aggregated evolve a demanding necessity for integrated monitoring of both soil and water systems in the regions proximal to thermal power stations, to relieve cumulative environmental and public health consequences.

Heavy Metal Accumulation in Medicinal Plants:

Accumulation Patterns and Associated Health Risks

Medicinal plants have a very good capability to absorb, accumulate, and transfer heavy metals from contaminated soil, irrigation water, and atmospheric deposition. A mechanism by which metals are mainly absorbed through the root system, primarily by means of mass flow and diffusion, is followed. The leaves directly absorb metal-containing dust from fly ash, thereby transferring metals to aerial tissues. In particular, this mechanism of the two-path exposure is significant in the areas in the vicinity of thermal power stations, in which a persistent quota of fly ash adds metals to both soils and air. As a result, medicinal plants growing in such environs usually are high in levels of non-essential and potentially harmful elements.



The investigation was detailed enough to report the detectable levels of arsenic (As), lead (Pb), cadmium (Cd), mercury (Hg), copper (Cu), nickel (Ni), manganese (Mn), zinc (Zn), and chromium (Cr) in all the plant species analysed; and some were close to or went beyond permissible limits for herbal materials accepted internationally [18]. Potential health hazards due to noncarcinogens, particularly Pb and Cd, as well as carcinogenic risks due to extended As and Cr exposure from regular contaminated herbal preparations, have been recognized on the estimated daily intake-based assessment on quantitative health risk [18]. These results suggest that chronic exposure should be considered important, particularly in communities that rely heavily on medicinal plants for their basic healthcare.

A similar comprehensive review focusing on medicinal plants within India reportedly showed wide contamination of Pb, Cd, As, and Hg, and the concentrations were found to be the highest in plant materials gathered in the industrial or peri-industrial areas [19]. Other contributing factors to contamination include the cultivation of medicinal plants on polluted soils, irrigation with polluted water, atmospheric deposition from industrial emissions, and inadequate post-harvest handling. These findings are notably relevant to regions around thermal power plants where soil contamination through fly ash and gaseous emissions is fairly persistent and long-lasting, in turn providing an unprotected pathway to medicinal flora and, in the long run, society.

Plants as Bioindicators and Phytoremediators

The high accumulation potential of metals in many species makes them ideal bioindicators for monitoring environmental contamination. However, the response of medicinal and non-medicinal species to site-specific pollution leads to a predictable accumulation pattern, making this plant an ideal bioindicator for monitoring heavy metal contamination in soil in concrete spatial and temporal terms [20]. These plants integrate metal exposure over time, overcoming the disadvantage of sampling in air or soil at a moment in time.

Plantago lanceolata and *Amaranthus retroflexus* are examples of species that are able to accumulate several metals, such as Pb, Cd, Ni, and Zn, in both the root and shoot [20, 21]. It is anticipated that it will be the longer-term storage of metals being stored in root tissue that will likely drive the concentration upward, based mostly on root-soil contact. However, translocation to the aerial parts depends largely on metal chemistry, plant physiology, and the external environmental conditions. Such functional traits of Csvl species make them good candidates for various strategies being applied in phytoremediation in contaminated soils.

In any system, one mention of favour does not mean that the entire environment is favourable, while one mention of preference does not mean that the whole system is favourable. Healing plants, when functioning as bio-indicators or hyperaccumulators, cause problems for their use as therapeutic materials. If plants are harvested from contaminated sites without ample inspections and proper quality controls, there are a plethora of risks to consumer safety. And the reason is that phytoremediation does benefit the environment; if we segregate the plants that are being used as healers from the remediation plant, we can avoid contaminated plant material being accidentally introduced into herbal products.

Mechanisms of Heavy Metal Stress and Phytochemical Responses:

Oxidative Stress and Antioxidant Metabolism

Heavy-metal exposure is known to trigger oxidative stress within plants by mainly increasing reactive oxygen species (ROS) generation, where superoxide anions, hydrogen peroxide, and hydroxyl radicals are highly significant [10]. Excessive intracellular ROS generation disrupts the redox balance, leading to lipid peroxidation, protein oxidative modification, enzyme inactivation, DNA damage, growth deceleration, and pathogen-induced metabolic malfunction.

Activation of a sophisticated antioxidant system that involves the active contribution of the non-enzymatic counterpart, i.e., phenols and flavonoids, as well as certain secondary metabolites, protects plants



against oxidative damage [11,22]. This role of scavenging ROS, membrane stabilization, and the chelation of metal ions allows molecules to neutralize and inactivate the actions of these molecules.

Under mental stress, maintaining redox homeostasis is carried out by phenolic substances and flavonoids. The early generation of these substances is hydrogen peroxide, which is needed to show the ability to release the metal ions, forming complexes and muting any reactivity in Fenton reactions with OH pollutants and metal ions that are harmful [23]. Many research studies have demonstrated that under conditions of heavy metal exposure, the presence of phenolics and flavonoids is greatly enhanced in these plants, thereby enhancing the study of these compounds regarding how they can work as another vital protective mechanism for oxidative stress [22, 24].

Modulation of Secondary Metabolites in Medicinal Plants

Admixtures of heavy metals can often instigate a significant difference in the production of secondary metabolites in medicinal plants. Experimental data revealed disturbance in the metabolic pathways leading to the synthesis of bioactive compounds under moderate stress conditions of metals, while specific metabolic pathways were completely suppressed upon severe or prolonged exposure to metals. For example, the stress of nickel on the plant *Impatiens balsamina* led to significant increases in total phenolic and flavonoid content and polar alkaloid content and consequently provided for better antioxidant activity, all of which suggest induction of defense-related metabolic pathways [25].

On the other hand, excess metal concentration can inhibit key enzymes in secondary metabolism, impairing the synthesis of terpenoids or specific alkaloids and diverting metabolic resources to elementary defensive mechanisms [12, 26]. The metabolic rejigging is not only quantitative but also qualitative, altering phytochemical synergy among bioactive ingredients.

Metal-induced perturbations in phytochemical profiles might change pharmacological properties of plants, affecting antioxidant, anti-inflammatory, antitumor, and antifungal activities [13,19]. Thus, the efficacy and safety of medicinal plants collected from metal-contaminated habitats end up being highly variable and confound their clinical utility.

Implications for Medicinal Plant Quality and Human Health:

Therapeutic Efficacy and Toxicity

While the accumulative higher accumulations of phenolics and flavonoids under metal stress may result in a substantial increase of the antioxidant capability and other potentials *in vitro*, they will be overshadowed by the toxicologists' fear of the bioaccumulation of heavy metals such as lead, cadmium, and mercury [18, 19]. Metals have the propensity to accumulate in the decoctions of herbs, their powders, and extracts, with such accumulation increasing in relevance, particularly by chronic exposure, where the metals gradually reach toxicological signs.

Conversely, our eyes are naturally shielded from the electromagnetic spectrum and can do so using perspective filtering devices, leaving open the possibility of altering our perspective mechanisms. When this filter is disrupted, we no longer arrive at any single perception-filtering technique and therefore no single perception [27].

Regulatory Challenges

Despite the establishment of maximum permissible limits for heavy metals in herbal raw materials and finished products by the WHO and national pharmacopoeias, standard enforcement remains questionable [19, 28]. Medicinal plants retrieved near the thermal power stations often join the informal or less regulated supply chains, with certainly deficient screens. Due to the inability to trace or provide quality assurance standard protocols, contaminated material is reaching the consumers, which in turn can be a seed of mistrust of the herbal products. Therefore, the situation connotes the potential importance of proper monitoring, certification of sites, and the use of advanced analytical techniques like ICP-MS in routine quality control methods.



Management, Mitigation, and Research Needs

The efficient mitigation of heavy metals' risk caused by thermal power plants calls for the integration of environmental regulation and medicinal plant management. This will play a vital role in checking the mobility of different bioactive constituents in the synch-rewat surface run-off [21, 29].

Further immobilizing toxins is a needed action in chemical remedial processes, with acts not limited to soil amendment, for managing toxic matter; these are required in specific geological locations under long-term manipulative assessment [30].

In the future, research efforts should focus on integrating metal accumulation studies with metabolomics and targeted in vitro and in vivo toxicity testing, conducting long-term monitoring in contaminated zones, and attempting to evaluate socio-economic impacts on the dependent societies in light of local medicinal plant resources. Such interdisciplinary efforts are necessary for the effective development of policies based on evidence that would ensure both environmental sustainability and public health interests.

Conclusion:

Heavy metal contamination caused by thermal power plants largely has its origin in the soil and water bodies that house them, primarily due to the release of toxic fly ash, bottom ash, and effluent containing lead, cadmium, chromium, nickel, mercury, and arsenic. Heavy metals actually are predominantly absorbed by medicinal plants growing in this heavy-metal-laced ambient from root uptake and aerial deposition, thereby often exceeding permissible safety levels. Simultaneously, when plants are exposed to heavy metals, oxidative stress ensues, stimulating defensive metabolic and biochemical mechanisms, which frequently go on to enhance the synthesis of more phenolics and flavonoids with antioxidant activities. Although it would suppress the properties of antioxidants, a newly produced set of metabolites is capable of alleviating the cellular damage caused by heavy metals; under normal conditions, this combination of actions would have compromised the effectiveness, safety, and therapeutics of these medicinal plant sources. This is why the prevailing message here is that medicinal plants in any environment shall become useful near thermal power stations if such an approach is worked upon by all the stakeholders to control environmental pollution, fine-tune disposal of ash and toxic wastage, and provide a protective buffer. On the other hand, improving awareness-raising and acceptance of controlled aspects of quality control, heavy metal screening, and tracing are to be made optional. The results of such a highly anticipated approach will require significant synergies and close interaction to re-establish a clear picture of the contamination parameter. Joint research across the fields of environmental chemistry, plant physiology, pharmacognosy, and public health would be a significant step forward to better understand contamination–phytochemical interactions so that science-based policies can be set up for the protection of human health and medicinal plant resources.

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