Environmental Fate of Metals around Indian Coalfields: Current Status and Remediation Strategies: A review

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Abstract

For the world economy, coal is still a crucial energy source. The two main techniques for extracting coal are surface and underground mining, each of which has advantages and disadvantages. Ecosystem losses, landscape modification, soil erosion, and alterations to the amount and quality of surface and groundwater are only a few of the environmental effects that surface coal mining may have. Furthermore, hazardous substances like radioactive elements, heavy metals, and other organic pollutants are discharged into the environment, ultimately impacting ecosystems and human health. The peculiar physico-chemical properties of northeastern Indian coals include low ash concentration and high sulphur, volatile matter, and vitrinite content along with a number of organic and mineral-bound elements, including Fe, Mg, Bi, Al, V, Cu, Cd, Ni, Pb, and Mn, are sensitive to the environment. These traits are linked to more serious environmental effects from mining and the use of coal in coal-based industries.

Keywords: metals, coalmining, soil erosion, remediation

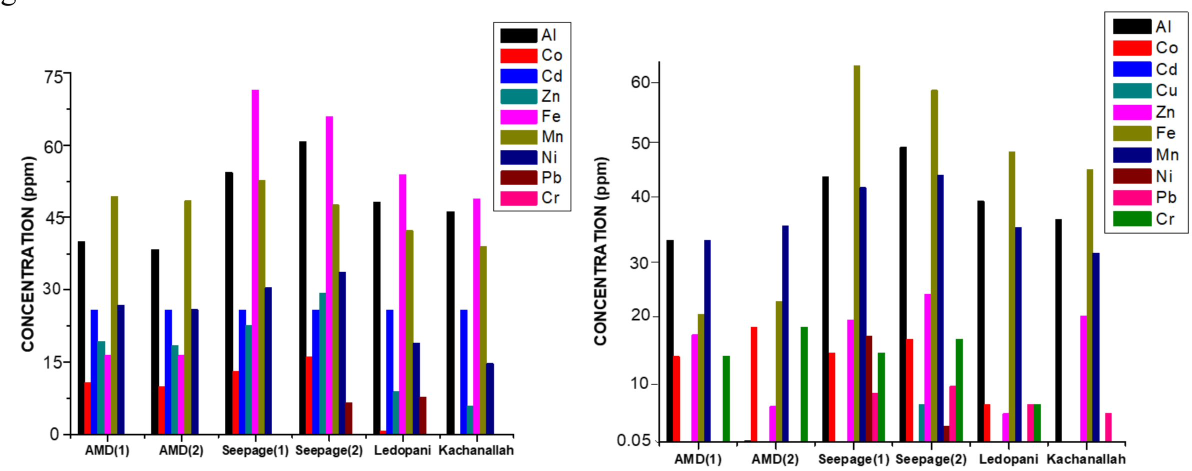
1. Introduction

The most plentiful fossil fuel in the nation is coal. India is the world's third-largest producer of coal, after the United States and China. It is a crucial component of the modern Indian economy. There are two main methods of mining coal: opencast mining and underground mining. Currently, opencast mines account for more than 85% of India's coal production. One kind of surface mining is opencast mining, which involves clearing the top soil, plant, and rock (also known as overburden materials) above the mineral deposits [1], which therefore impacts

the fertility of nearby lands [2]. Fig.1 shows the opencast mining of Northeastern coalfields. The process of mining coal produces a large amount of waste rocks and mined spoils, which oxidise in the atmosphere and discharge effluents that are heavy with metals into the surrounding area. The quality of shallow groundwater and surface waterways close to the mines is impacted by these effluents.

Fig.1: **Open cast coalmining at Ledo coalmine (Makum) of Northeastern coalfields [22]**

Additionally, the physical, chemical, and microbiological properties of soil undergo a number of modifications. According to Masto et al. (2015) [3], soil quality is one of the important factors for assessing environmental pollution in the coal mining region. A wide area is adversely impacted by fine dust particles surrounding coal mining. Toxic trace elements such as arsenic, cadmium, lead, zinc, chromium, magnesium, and their compounds may occasionally be elevated in these dust particles. When this kind of dust is placed on land, it degrades the soil's quality and agricultural output, as well as the health of grazing animals [4]. Metalloids, transition metals, basic metals, lanthanides, and actinides are all considered heavy metals. Among these, Cr, Mn, Co, Cu, Zn, Mo, Hg, Ni, Sn, Pb, Cd, Sb are the main elements that are recognised as heavy metals. Toxic metals, precious metals, and radioactive nuclides are the three primary categories of heavy metals of concern. Mercury (Hg), chromium (Cr), lead (Pb), zinc (Zn), copper (Cu), nickel (Ni), cadmium (Cd), arsenic (As), cobalt (Co), and tin (Sn) are examples of toxic metals that pose serious concerns to human health and the environment. Pb, Hg, Cd, and Cr are especially well-known for having high levels of toxicity. Additionally, lead, mercury, and cadmium are frequently referred to as the big three elements which are particularly prominent due to their substantial environmental impact and associated health risks [5]. The liquid mine discharges from coalmines typically contaminate the local surface and ground water due to high amounts of TDS, TSS, and heavy metals. Because coal is extremely soluble in nature, the complex process of extracting it produces heavy metals and dangerous toxicants. An acidic environment is created in the soil and water bodies by the emission of metals including Fe, Cu, Mn, Co, Ni, Pb, Zn, and other mineral dusts [6,7]. Because of their excessive accumulation, biomagnification, and toxicity, heavy metals in water are among the most dangerous contaminants [8,9]. While some metals (including Cu, Co, Fe, and Mn) are necessary for metabolic processes in living things in trace amounts, higher quantities of these metals can be harmful to health [10]. Even at low quantities, trace metals can be harmful [11] and can upset the aquatic ecosystem's food chain by harming fish, birds, and mammals, including people [12]. On terrestrial invertebrates and vertebrates, metal pollution produces harmful consequences like cellular damage, carcinogenesis, and neurotoxicity [13]. Even though some metals are essential as trace elements for living things, they can either accumulate in living things above a certain concentration and have harmful effects, or they can change into other compounds in the environment, which can occasionally result in the formation of toxic and water-soluble metal compounds. Because of this, heavy metals and trace elements are categorised as either vital or non-vital based on how much they contribute to biological processes [14]. High amounts of harmful metals that were leached from acid mine drainage (AMD) were found to be contaminating water bodies near the coal mining region of Jaintia Hills, Meghalaya. AMD is characterised by low pH, elevated sulphate, iron, aluminium, and other hazardous elements [15]. High iron levels were found in the mine water of the East Bokaro coalfield [16], whereas high iron and aluminium concentrations were found in the West Bokaro coalfield. It was observed that the metals like Fe, Mn, Ni, Al often exceed safe drinking water limits [17, 18]. The sub-bituminous coals from the Makum coalfield, Assam, revealed that Cd is bound to either organic or mineral matter, Fe, Co, Ni, Cu, and Zn are largely mineral bound, and Mg, Ca, and Mn are organically bound [19,20]. The propensity of these coals for atmospheric weathering was demonstrated by their aqueous leaching, and the very acidic water created during the process increased the mobilisation of related trace and heavy metals (Fe, Mg, Bi, Al, V, Cu, Cd, Ni, Pb, and Mn) above the regulatory values [21,22]. Coals from the Makum coalfield in Assam had values of Cr, Mn, Ni, Cu, Zn, As, and Pb of 5, 23, 5, 2, 27, 1, and 4 mg/kg, respectively. Coals from the Makum coalfield in Assam had values of Cr, Mn, Ni, Cu, Zn, As, and Pb of 5, 23, 5, 2, 27, 1, and 4 mg/kg, respectively. These elements were found in coals from the Moulong Kimong coalfield in Nagaland with concentrations of 4, 2289, 3, 2, 49, 2, and 1 mg/kg, respectively [23]. In the overburden of the northeastern Makum coalfields, the concentrations of Cr, Cu, Mn, Ni, Pb, and Zn are higher than their corresponding crustal abundances. Pb, however, is more abundant in coal than it is in the crust. According to the leaching experiment, overburden with high pyrite has a greater ability to release metals than overburden with low pyrite. The concentrations of Mn, Ni, and Pb in leachates are determined to be significantly higher than the corresponding water quality guidelines. Siderite dissolution is observed to be linked to abnormally high Mn concentrations. Ni is released in a noticeably high concentration from coal [24]. It is found that the concentrations of most of the metals like Cd, Pb, Ni etc. in AMD and seepage and nearby areas of Ledo coalmine of Northeastern coalfields during monsson are more than in non-monsoon seasons [22]. Fig.2 shows the change in metal concentations during monsoon and non-monsoon seasons.



[a] [b]

Fig.2: Change in metal concentrations at Ledo coalmine of Northeastern coalfields in monsoon [a] and non-mosoon [b] seasons [22]

Since aquatic environments are thought to be more susceptible to contamination exposure, heavy metal contamination is one of the main water pollution issues in mining divisions [25, 26]. The water is harmful to the ecosystem and human health due to the high toxicity of heavy metals, even at low quantities.

1.1.Metal Contamination Sources

By accumulating overburden and releasing massive amounts of mine debris and dust, coal mining alters the local terrain and increases the trace metal load in the surrounding area. The ecology has been adversely affected by the release of acid mine drainage (AMD) water from mines and mining wastes [27]. Hazardous trace metals like mercury are released into the atmosphere by active coal mine fires. Fly ash produced by coal-fired thermal plants enriches the nearby soils with metals. The aquatic flora and wildlife are impacted by the trace metals released into groundwater, lakes, and streams by the runoffs from coal washeries [28]. Coal mining releases metals via acid mine drainage, processing, and fly ash, with geogenic factors and vehicular emissions contributing. Concentrations rise pre-monsoon due to reduced dilution, affecting groundwater pH (acidic to alkaline) and sulfate levels. The coal slurries produce high levels of Se. The release of mercury from burning coal can cause a severe health problem [29]. The hazardous toxic metals like As, Se, and Cd, are produced from fly ash produced by coal-based power plants. The primary source of contaminants, particularly heavy metals in water, is typically mine tailings and other mining-related activities [30, 31, 32]. The air containing mine dust, transportation activities, and the discharge and dispersion of coal mine wastes are the three main sources of toxic metals in the soil of the mine environment [33]. The possible negative ecological effects of heavy metal-contaminated soil near coal mining regions have made it a key environmental concern. Large amounts of heavy metals are deposited in trash dumps due to mining activities [34]. Because of leaching and pre mining activities, mine-degraded soils also contain metal pollutants [35].

1.2.Environmental Fate and Impacts

Metals mobilize in water systems, with Fe > Mn > Zn > Cr > Pb > Cu > Cd order in affected areas; mine water shows higher toxicity (80% high water hazard index). Health risks include non-carcinogenic effects from ingestion, higher for children, alongside biodiversity loss and land degradation in regions like Jharia [36]. Sub-bituminous tertiary coal with low ash concentration and significant sulphur, volatile, and vitrinite content can be found in large quantities in northeastern India. The inclusion of Fe, Cu, Cd, Ni, Pb, and Mn in bonded mineral form is harmful to the environment, even though these characteristics make the coal desirable for industry [37]. Coal is the primary source of mercury and other hazardous elements in the surrounding soil of coal mining regions [38]. Mercury has been regarded as a worldwide pollution because of its capacity to travel over great distances (1000 km) in the atmosphere [39]. Because mercury can interfere with important enzymatic processes at the cellular level, its toxic effects can harm the neurological system, brain, heart, kidneys, lungs, and immune system [40]. The combustion of fossil fuels, particularly coal and mining operations, is the cause of arsenic (As) accumulation in urban environments [41]. In addition to being a concern to the environment, cadmium is a poisonous metal. Coal mining operations and coal dust deposition are the causes of the higher concentration of Cd in the surface soil. The divalent form of cadmium (Cd^{2+}) is found in soil at concentrations of 0.1–1 mg/kg and can reach up to 3 mg/kg [42]. Researchers [43] observed that exposure to lead can harm the nervous system, exposure to mercury can harm the kidneys, and exposure to cadmium can demineralise bones. For living things to function normally, certain concentrations of metals including Fe, Cu, Mn, Zn, Co, and Mo are thought to be necessary. However, high levels of these necessary metals in drinking water can have harmful consequences and lead to a number of illnesses, including typhoid, cholera, dysentery, diarrhoea, and other neurological disorders. According to Wahlqvist et al. [44], elevated Co concentrations may result in lung illness, asthma, contact allergies, and an elevated risk of cancer. While Ni may be the cause of contact dermatitis, heart disease, asthma, lung fibrosis, and respiratory tract cancer, Mn is linked to manganese-induced parkinsonism and neurological symptoms [45]. Metals such as Fe, Cu, Mn, Ni, Pb, Zn, Cd, As, and Hg in Indian coalfields provide significant environmental hazards, chiefly via Acid Mine Drainage (AMD) and coal ash leaching, which contaminate soil, groundwater, and rivers, disrupt ecosystems, and adversely affect human health. These metals accumulate in soil and water, affecting aquatic life, soil microbiology, and food chains. Research has shown that areas like Talcher and Korba have significant pollution levels, which calls for remediation and water quality mitigation techniques [15]. It has been demonstrated that heavy metals (As, Cd, Zn, Pb, and Cu) lower soil microbial populations by interfering with cellular structures and functions, which in turn prevents microbial activity [46]. Long-term exposure to heavy metals has also been shown to change the structure of microbial communities, decreasing variety and leading to the extinction of some species, which eventually deteriorates soil quality. Interestingly, compared to actinomycetes and bacteria, fungi exhibit higher tolerance to Pb, Cd, Hg, and As [47]. By entering the body through a variety of mechanisms, heavy metal pollution poses serious health concerns to humans and interferes with the regular operation of groundwater systems [48]. Human health can be negatively impacted by exposure to toxins and heavy metals through skin contact or water consumption, which can result in acute or toxic effects [49]. Iron (Fe), nickel (Ni), cadmium (Cd), lead (Pb), mercury (Hg), and arsenic (As) are among the metals in Indian coalfields that are mobilised by mining, resulting in Acid Mine Drainage (AMD), which seeps into soil and water and contaminates surface and groundwater. This contamination affects food chains, degrades ecosystems, disturbs aquatic life, damages soil bacteria, and offers major health concerns to humans through drinking water. Significant pollution zones have been found in places like Talcher and Wardha Valley. The effects include soil acidity, decreased organic matter, and changed microbial communities[50].

1.3.Current status: contamination and impacts

Siddiqui et al. [51] (2020) conducted more research on the metal contamination in Jharia CF soil and discovered that trace metal concentrations were lower than the geological background value. However, multivariate statistics and several pollution indices showed that the majority of the soil had a moderate level of contamination. The present status of metal contamination has been documented across major coal belts in India. Umaria Coalfields (Madhya Pradesh): Groundwater was discovered to contain alarmingly high amounts of manganese, iron, and aluminium, frequently beyond BIS guidelines, rendering the water unsafe for human consumption in many places. Raniganj Coalfield (West Bengal/Jharkhand) region has considerable non-carcinogenic and carcinogenic health risks through ingestion, skin contact, and inhalation due to extensive soil contamination with lead and cadmium. The Talcher Coalfield (Odisha) has found to be contaminated surface water. Due to surface runoff and dilution effects, high quantities of iron, aluminium, and selenium are common and exceed regulations, especially during the monsoon season. The hot spots of

Korba Coalfield (Chhattisgarh): Hot spots are located next to fly ash dykes of power plants, and sediments show high mean concentrations of vanadium, chromium, manganese, cobalt, copper, zinc, lead, and uranium [52].

High levels of heavy metals like cadmium (Cd), nickel (Ni), chromium (Cr), arsenic (As), and mercury (Hg) have been found in soil and water in Northeast Indian coal mines. These metals pose serious health risks (unacceptable carcinogenic/non-carcinogenic risks for children and adults) and cause ecological damage, such as river contamination (Dikhow River) due to Acid Mine Drainage (AMD) and mining operations, particularly in places like Assam's Makum coalfields. Better management and awareness are required, even though certain places have moderate to severe pollution (the highest levels of Cd and Ni)[53]. According to recent studies, opencast mining and acid mine drainage have seriously contaminated the soils and groundwater surrounding Indian coalfields including Raniganj, Jharia, and Umaria with heavy metals. Important elements like iron, manganese, cadmium, lead, and zinc surpass permissible limits, endangering human health and the environment, especially children[52].

1.4. Remediation Advances

In Ledo Coal Fields, vermicomposting shows promise as a sustainable method for mining tailing soils. It improves soil fertility for plant development and lowers the bioavailability of heavy metals (e.g., through the Risk Assessment Code). For the economical and environmentally responsible removal of metals such as Cu, Ni, and Pb from contaminated locations close to coal plants, phytoremediation with hyper-accumulator plants is advised. In order to reduce surface pollution, parliamentary guidelines support relaxing approvals for low-impact underground mining [54]. The most efficient and sustainable methods for cleaning up heavy metal-contaminated coal mine soils include vermicomposting and phytoremediation, especially in Indian contexts like Ledo and Raniganj coalfields. These biological techniques surpass conventional chemical stabilisation in terms of long-term performance by lowering metal bioavailability, improving soil fertility, and promoting plant development without requiring significant energy inputs [55]. Metals like cadmium, lead, and zinc are extracted from mine tailings by hyper-accumulator plants like sunflower and Azolla pinnata; pot tests in Jaintia Hills have demonstrated improved removal using phytoextraction. By converting metals into less hazardous forms, microbial-assisted phytoremediation increases efficiency and permits the reuse of biomass for charcoal or biogas in a circular economy [56, 57]. In addition to improving nutrients, water retention, and bulk density, adding 20–40% vermicompost to mine tailing soils reduces heavy metal mobility (for example, by lowering the Risk Assessment Code) and supports crops like tomatoes and okra in Ledo fields. By encouraging earthworm activity for the decomposition of organic debris, this environmentally friendly addition performs better than bare soil regeneration [58]. Vermicompost-amended soils at Ledo Coal Fields (2025) facilitated phytoremediation using plants such as tomato (Solanum lycopersicum) and okra (Abelmoschus esculentus), reaching 30% vermicompost ideal for metal immobilisation and growth, while mostly vermicomposting-focused. Over 120 days, this improved bioavailability reduction for several metals was observed. Microbiome improvements have been shown to be essential for rebuilding mine soils, and in situ microbial remediation speeds up the synthesis of soil aggregates and the cycling of nutrients in coal gangue. Integration of biochar minimises erosion on remediated sites by retaining moisture and sequestering metals [58].

2. Conclusion:

This review demonstrates that metals released from Indian coalfields follow complex pathways through air, soil, water, and biota, resulting in persistent hotspots of contamination that frequently exceed ecological and human health thresholds. Synthesizing evidence from major coal belts such as Jharia, Raniganj, Singrauli, Talcher, and Northeastern coalfields reveals a consistent pattern of multi-metal pollution (e.g., Fe, Mn, As, Pb, Cd, Cr, Zn) driven by acid mine drainage, overburden weathering, fly ash dispersal, and coal-fire emissions, with particular vulnerability of groundwater and agricultural soils surrounding mine leases. Taken together, the current status clearly indicates that management remains largely reactive and site-specific, with fragmented monitoring, limited speciation data, and inadequate consideration of metal bioavailability, trophic transfer, and cumulative risk to local communities. A critical gap is the lack of long-term, integrated datasets linking mining intensity, geochemical conditions, and health outcomes, which hampers robust regional risk assessment and prioritization of intervention zones. At the same time, the review highlights that a portfolio of remediation strategies—phytoremediation, vermi- and bio-remediation, biochar- and compost-based amendments, passive treatment of acid mine drainage, and engineered covers—can substantially reduce metal mobility and toxicity when deployed in a site-specific and combined manner. Emerging work from Indian coal areas shows that plant–microbe systems, organic amendments, and low-cost passive technologies not only immobilize or extract metals but also rebuild soil structure, carbon stocks, and microbial diversity, aligning reclamation with broader land restoration and climate goals. Embedding these measures within regulatory standards, mine closure plans, and community-centered decision-making can transform coalfield regions from long-term metal sinks into progressively recovering socio-ecological systems. In this context, future research should prioritize multi-metal speciation, coupled hydrogeochemical–ecotoxicological modeling, field-scale trials of combined green remediation approaches, and decision-support tools that help regulators and industry stakeholders select cost-effective, socially acceptable strategies for different Indian coalfield settings.

Declaration of Conflict of Interest- The authors declare that there is no conflict of interest.

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